ALLIS-CHALMERS

ELECTRICAL REVIEW

June • 1944

Aluminum reduction is one of the U. S. plants involves this imposing battery of 24 twelve-tank Excitron mercury arc rectifiers, which furnish direct-current to two potlines in which aluminum oxide is reduced. On the left are high-speed anode circuit breakers; on the right, cathode breakers.

Yes, Men Make Motors!

NO MACHINE KNOWN can duplicate the skill of Sam Meister, left, of Allis-Chalmers Norwood Works.

Holding an acetylene torch in his right hand, a silver alloy rod in his left, Sam silver-brazes end connections of Allis-Chalmers' "Indestructible Rotor."

Round and round the connections he works — expertly flowing in molten alloy to form a joined structure that can withstand as much heat as though it were a single die-casting.

No machine can do that job — and no machine can fully test how well it is done.

There's only one test . . . wait 5, 10, 15 years and *see.*

And that's the test in which Allis-Chalmers motors have proved over the years that they're *great* motors. That's why you hear it said so often: *"You can depend on Allis-Chalmers Motors!"*

• • •

YES, HUNDREDS of Allis-Chalmers men—craftsmen like Sam Meister — know they have a big personal stake in every Allis-Chalmers motor. When they build a great motor for you, they're making a *friend* . . . and they know that's something no company and its workers can have too many of.

Next time *you* need great motors contact our district office. Or write direct to ALLIS-CHALMERS, MILWAUKEE 1, WISCONSIN.

A 1730

WE WORK FOR VICTORY — WE PLAN FOR PEACE

♪ *Tune in the Boston Symphony, Blue Network, Saturday at 8:30 pm, EWT.*

YOU CAN DEPEND ON ALLIS-CHALMERS MOTORS

Vol. IX . . . No. 2

June, 1944

Allis-Chalmers
Electrical Review

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ALLIS-CHALMERS

ELECTRICAL REVIEW

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NOW INSTRUMENT TRANSFORMER STANDARDS MAKE SENSE!

A. S. A. standards clear the picture on problems in electrical measurements . . . where instrument transformers are just as important as the meters.

F. E. Davis

COMMONWEALTH AND SOUTHERN CORPORATION

The importance of metering installations, particularly for billing purposes, is often underestimated. For two vital reasons the accuracy of power-measuring meters must be assured—they determine the income to the supplier, and they determine whether or not the power user obtains the full measure of service for which he pays.

Measurement of large blocks of power at higher voltages requires not only watthour meters, demand meters and related equipment, but instrument transformers as well. In such installations, the instrument transformers are just as important a part of the meter installation as the meters themselves. Instrument transformers for such use, therefore, should be carefully chosen, not only from the standpoint of their accuracy under the imposed conditions, but from the standpoint of their ability to give trouble-free service continuously over long periods of time.

Anyone dealing with electrical measurements should be thoroughly acquainted with the standards of the American Standards Association, under which modern instrument transformers are manufactured today. Revised from the original compilation of 1940, the standards now provide a highly satisfactory criteria by which the performance of these transformers can be rated or specified.

Major revisions appearing in the latest publication, C57.1-1942, deal mainly with insulation ratings, accuracy under metering and relaying conditions, and nameplate data. Other helpful revisions of a more minor nature reduce the number of so-called preferred ratings, unify the so-called standard instrument transformer burdens, specify the thermal and mechanical limits of current transformers for short time ability to withstand heavy currents and correlate voltage rating and insulation levels for low frequency voltage tests and impulse tests.

AT LEFT: Motor for a piercing mill drive — on test here — will help to turn steel billets into steel tubing. It is a 1500 hp, 120 rpm unit, with 300 percent maximum torque.

Insulation Classes

Among the most important of the A.S.A. sections are 4.050 and 4.051, covering the insulation classes for instrument transformers. With much of the indecision of the original proposal eliminated, the various standard insulation classes and apparatus ratings now have definite meaning, so that nameplates actually show what the apparatus is. Revisions in Table 7, for example, remove the difficulties formerly found in attempting to correlate current or potential transformers in any of the lower insulation classes with actual test voltage or with system voltages on which they could be adequately used.

Table 9, which is completely new, has been included to correlate preferred ratings for potential transformers and their insulation classes and test voltages. This has been done to eliminate the former ambiguity of the classes and ratings, recognizing only a minimum number of ratings and classes based on present practice. In this table, transformer ratings are provided for both delta and wye connections for both 3 and 4 wire, 3 phase systems of the more usual ratios, the same transformers not necessarily being suitable for both types of service. For instance, a 20/1 ratio transformer in the 2.5 kv insulation class is provided for delta, 3 wire, 3 phase connection on a 3 wire, 3 phase delta connected system of 2400 volts. This transformer should not be used for wye connection on a 4160 volt, 4 wire, 3 phase system. Such service requires more insulation, and the transformer for this service is provided for in the next higher or 5 kv insulation class. A similar situation exists for the 40/1 and 60/1 ratio ratings. This diversity is required by present practice, although where the possibility exists that present delta systems may be reconnected wye at some future time, the transformer of suitable ratio in the higher insulation class will likely be used exclusively, since it may be reconnected with the system as required.

In the insulation classes 25 kv and above, transformers for both delta and wye connections are listed. In transformers designed for wye connection, a provision for 69.3 volts in the 25 kv class and 66.4 volts

in the classes above 25 kv for line to neutral secondary voltage is made by means of a tap in the secondary winding of such transformers. The full windings provide 120 and 115 volts secondary line-to-neutral voltages, respectively, in the wye connection at rated voltages. In transformers designed for use on delta connected systems, the secondary voltage of 120 and 115 volts line-to-line at rated voltages, respectively, is provided.

It will be noted that the use of the tapped secondary winding on transformers designed for wye service will eliminate the necessity for two lines of transformers to provide 120 or 115 volts secondary line-to-line and these same voltages line-to-neutral. Provision is also made that such transformers designed for use on 3 wire ungrounded or impedance grounded systems (or on a 4 wire system where the ground may be disconnected) should have magnetic

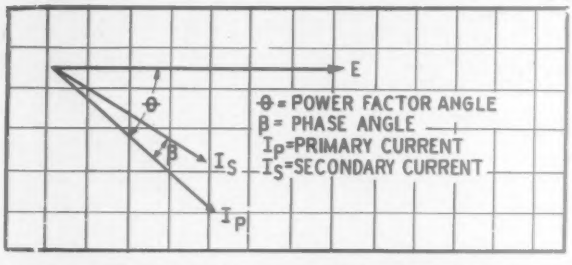


Fig. 1 — Relationship of Ratio Correction Factor (RCF) and Transformer Correction Factor (TCF) in procedure for specifying the accuracies of current transformers for metering service.

induction low enough to enable them to operate continuously at line-to-line voltage. The performance of these two-ratio transformers is to be based on the higher ratio.

In a similar manner Table 10 provides a correlation of the insulation classes for current transformers with the maximum line-to-line voltage and dielectric tests. In interpreting this and other tables in this section, it should be considered that voltage ratings are based on 3 phase, line-to-line values and that line-to-neutral or ground voltages are, in effect, the rated voltages divided by the square root of three. Thus for a single phase circuit with one line grounded, say of 4.8 kv, instrument transformers in the 8.66 kv insulation class will be required. For a 4.8 kv circuit, 3-wire, 3 phase isolated neutral, the 5 kv insulation class is required. For an 8.3 kv, 4 wire, 3 phase circuit (with or without grounded neutral—4.8 kv line to neutral voltage) the 8.66 kv class is required. Also, a transformer in the 5.0 kv insulation class should not be used on a circuit of more than approximately 3000 volts from line-to-neutral, whether wye or delta connected, or 3 or 4 wire, 3 phase or 2 wire, single phase.

For present 3 wire, 3 phase lines or systems that may possibly be converted to 4 wire, 3 phase in the future, consideration should be given now to the use of instrument transformers which will be suitable for the proposed future service. This is similar to the case with power transformers which, however, in the lower voltage classes are generally suited to either the 4 wire or 3 wire, 3 phase connection, while the instrument transformers are not necessarily so.

Metering accuracy

The method used for specifying the accuracies of current transformers for metering service is revised to take into account the effect of ratio errors and phase angle on the accuracy of measurement as it depends on the power factor of the metered power load. Thus, with the limits of ratio deviation and phase angle, as well as a range of load power factors specified, the class designation represents the limit of deviation of measurement accuracy from 100 percent within such limits.

In the new specification, Ratio Correction Factor (RCF) has been used instead of ratio error and a new factor, Transformer Correction Factor (TCF) has been used to denote the effect of ratio error, phase angle and load power factor within the limits set on the accuracy of measurement. These quantities are linked by the formula:

$$\beta = 2{,}600\ (\text{RCF-TCF})$$

where β is the phase angle in minutes and 2,600 is a factor depending upon the load power factor range which range has been chosen from 0.6 to unity for the purposes of the standard.

This relationship is rather simply developed for a current transformer of 1 to 1 ratio assuming no potential error. Referring to Fig. 1:

$$\text{Actual power} = EI_p \cos\phi$$

$$\text{Indicated power} = EI_s \cos(\phi-\beta)$$

$$\frac{\text{Actual power}}{\text{Indicated power}} = \text{TCF by Definition}$$

$$\frac{I_p}{I_s} = \text{RCF by definition}$$

$$\text{Then TCF} = \text{RCF}\,\frac{\cos\phi}{\cos(\phi-\beta)}$$

$$= \text{RCF}\,\frac{\cos\phi}{\cos\phi\cos\beta + \sin\phi\sin\beta}$$

If the phase angle is small:

$\cos\beta = 1$ (very nearly) and $\sin\beta = \beta$ in radians (very nearly).

$$\text{TCF} = \text{RCF}\,\frac{\cos\phi}{\cos\phi + \beta\sin\phi}$$

$$\text{RCF} = \text{TCF}\ (1 + \beta\tan\phi)$$

$$\text{And } \beta = \cot\phi\,\frac{\text{RCF-TCF}}{\text{TCF}}$$

RCF cannot deviate from unity any more than the TCF because of the limit of unity for load power factor, and if this deviation is small:

$\frac{\text{RCF-TCF}}{\text{TCF}}$ may be taken as equal to RCF-TCF without affecting the value of the phase significantly when the phase angle is relatively small:

Thus $\beta = \cot\phi$ (RCF-TCF) where β is in radians and $\beta = 3{,}438\cot\phi$ (RCF-TCF) where β is in min-

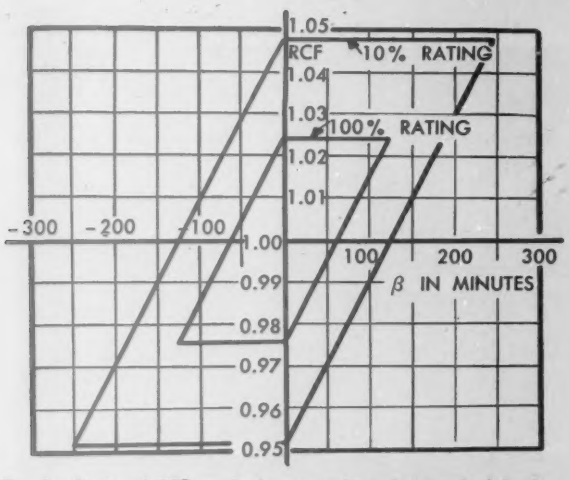


Fig. 2 — Limits of RCFs and phase angels under standard burden and percent rated current for current transformer accuracy, Class 2.4.

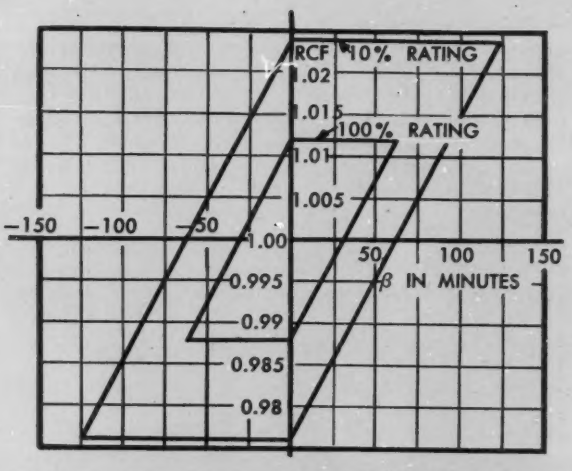


Fig. 3 — C. T. Class 1.2 ratings are represented by these boundary parallelograms at 10 percent and 100 percent of the rated current.

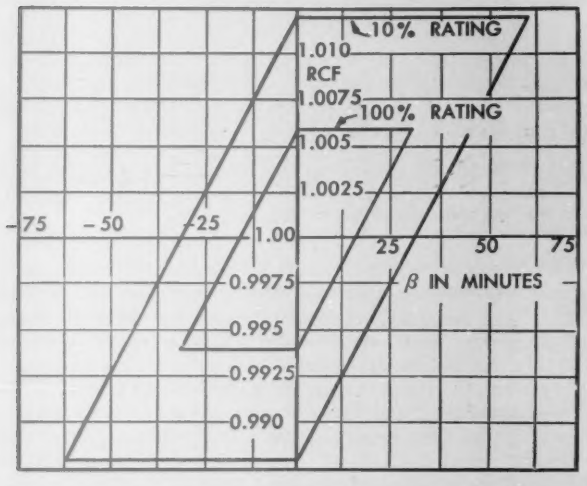


Fig. 4 — C. T. Class 0.6 accuracy ratings plotted in rectangular coordinates.

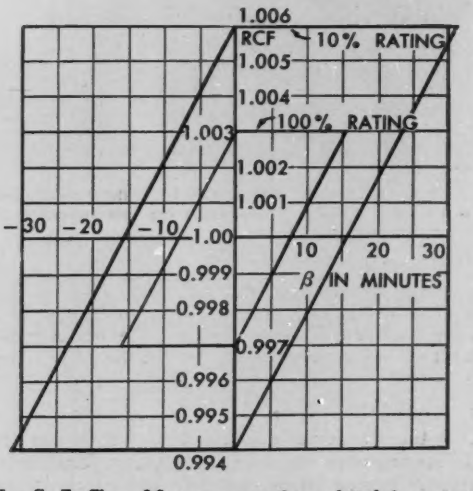


Fig. 5 — C. T. Class 0.3 accuracy ratings plotted in rectangular coordinates.

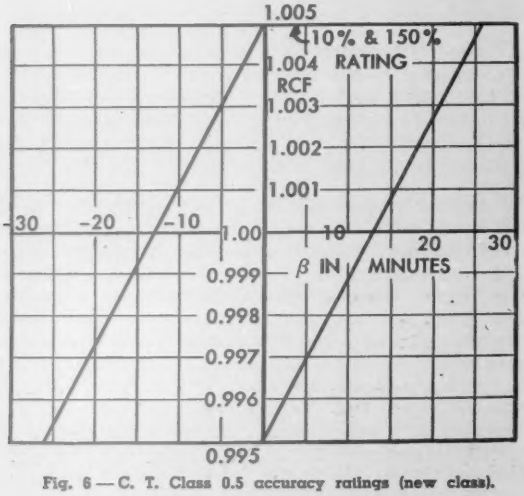


Fig. 6 — C. T. Class 0.5 accuracy ratings (new class).

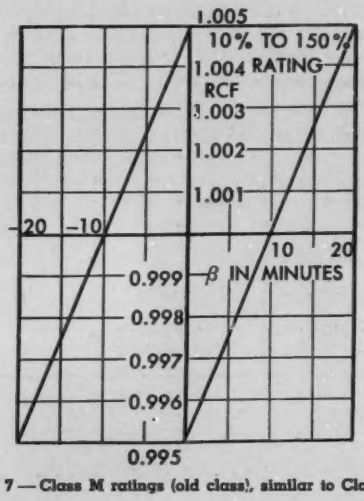
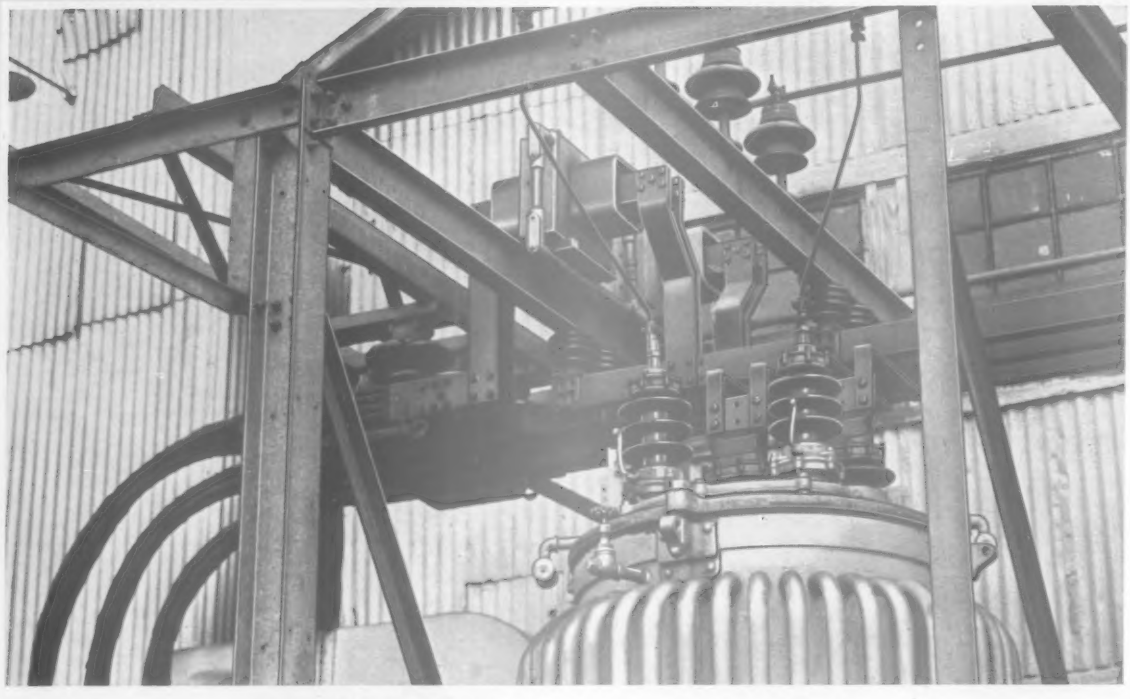


Fig. 7 — Class M ratings (old class), similar to Class 0.5.



CURRENT TRANSFORMERS like these dry type units on a southern utility system are now completely rated by recently revised A. S. A. standards.

utes; ϕ has been specified as Cos^{-1} 0.6 or 53° 8′ and the limits of TCF will not be exceeded between $\phi = 0°$ and $\phi = 53° 8'$.

$\beta = 3{,}438$ Cot 53° 8′ (RCF-TCF)

$\beta = 2{,}600$ (RCF-TCF), nearly

This classification of limits, when plotted in rectangular coordinates results in boundary parallelograms for each class at 10 percent and 100 percent of rated current, within which the actual RCFs and phase angles under the given conditions of standard burden and percent rated current must fall when plotted if a given transformer is to be given the accuracy rating of that class. Figs. 2, 3, 4, 5 and 6 show the various new accuracy classes plotted in this manner.

Figure 7 shows former Class M plotted in this same manner as a matter of interest and it will be noted that former Class M was specified in a quite similar way to that used for all of the new accuracy classes and that the present method, therefore, is not entirely new.

Present classes 1.2, 0.6, 0.3 and 0.5 correspond, in general, to former classes 1, ½, ¼ and M respectively, and, although the limits of RCF deviation are slightly wider and phase angle limits are considerably extended, the effect of these factors on meter registration in a given class are less and rather definitely fixed. Present class 2.4 has been added with wider limits than any of the former classes to permit the rating for metering accuracy of certain current transformers with comparatively large effect on metering accuracy, such as some bushing and similar types.

The metering accuracy class of a current transformer is to be specified as 0.3 B-0.5 or 0.6 B-2, etc. The 0.3 B-0.5 class means that at the 12.5 volt-ampere burden the transformer will not affect the accuracy of a wattmeter or watthour meter more than ± 0.3 percent at 100 percent rated current or ± 0.6 percent at 10 percent rated current with power factor of the metered load in the range from 0.6 to 1.0. Thus the limits of RCF are the same as for TCF, as shown, and the limits of phase angle are ± 15.6 minutes at 100 percent and ± 31.2 minutes at 10 percent rated current, but these values vary with value of RCF within limits specified.

This method of accuracy specification should be of major interest to the metermen of the industry since it is significant and rigid and associates the effect of instrument transformer ratio errors and phase angles on the accuracy of measurement directly with the accuracy classification nomenclature.

The same method has been used for specifying the accuracy classes for potential transformers as for current transformers. However, since a positive phase angle for a potential transformer has the opposite effect on the accuracy of measurement as a positive phase angle for a current transformer, the formula linking the values of phase angle, RCF and TCF, has a slightly different form and:

$\gamma = 2{,}600$ (TCF-RCF)

Figures 8, 9, and 10 show the accuracy classes for potential transformers plotted in the parallelogram form similar to those for the current transformer

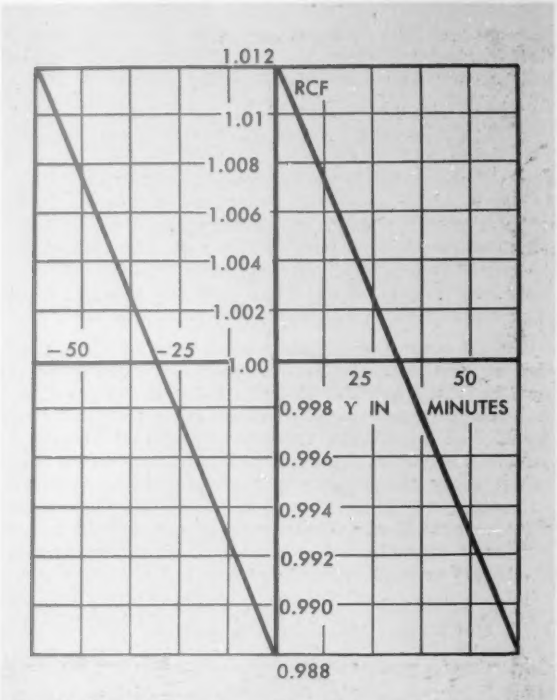


Fig. 8 — Potential Transformer Class 1.2 in parallelogram form.

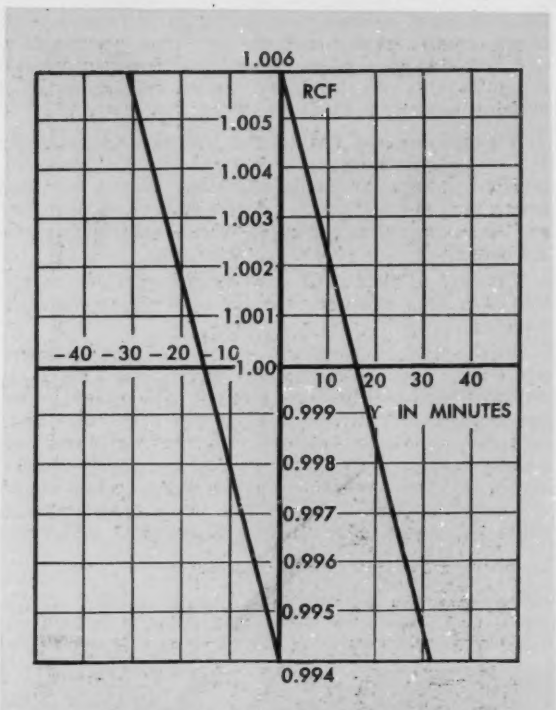


Fig. 9 — Class 0.6, showing limits of characteristics.

classes. Only three classes are set up since the 2.4 and 0.5 classes for current transformers are not necessarily required for potential transformers used in measurement work.

Relaying accuracy

The former proposed standards did not include standard accuracy classes for current transformers for relaying service, therefore this section is entirely new. It is the result of a rather ambitious undertaking to provide a much needed method for comparing the performance of current transformers, under steady state conditions, at the high currents and overloads involved in protective relaying. It establishes in a general way limits of errors which are not to be exceeded by transformers placed or rated in a specified accuracy class.

Current transformers are divided into two general groups for accuracy rating purposes in relaying service. The first group is described as those having high internal secondary impedance and includes most of the wound primary and some "through" types with good metering accuracy. The second group is described as those having low internal secondary impedance and includes some "through" and most bushing types. The term "internal impedance" has been used to identify "that elusive characteristic of current transformers through which the exciting current required for a specified secondary induced voltage becomes different for different values of secondary current."*

Thus a transformer of the first group above, designated by the letter H, can maintain a relatively con-

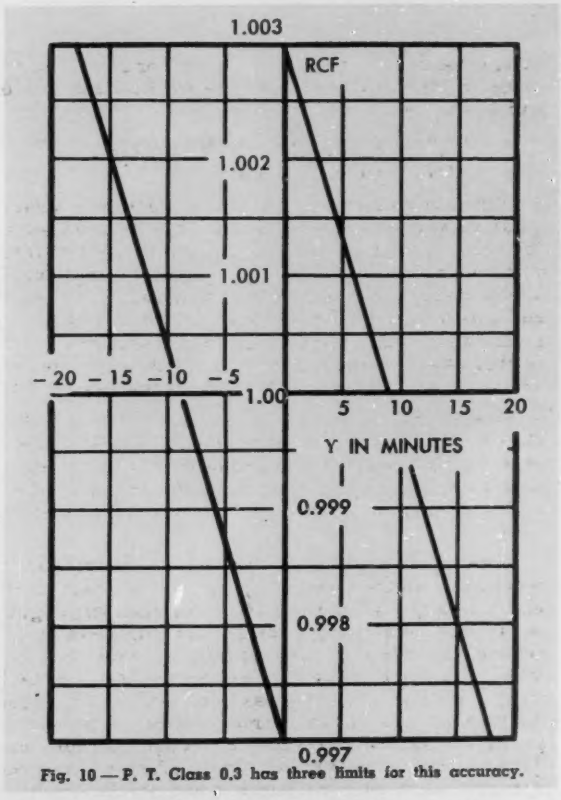


Fig. 10 — P. T. Class 0.3 has three limits for this accuracy.

* Reference—AIEE Paper 42-116—Clem, Neher and Harder.

stant terminal voltage over the range of from 5 to 20 times rated current due to the fact that internal voltage drop decreases more rapidly than induced secondary voltage as the secondary current and the value of exciting current decrease.

Transformers of the second group, designated by the letter L, do not, as a rule, have this compensating internal voltage drop and therefore cannot be rated over a range of secondary values as can the first group, and the range of rating is preferable where it can be applied.

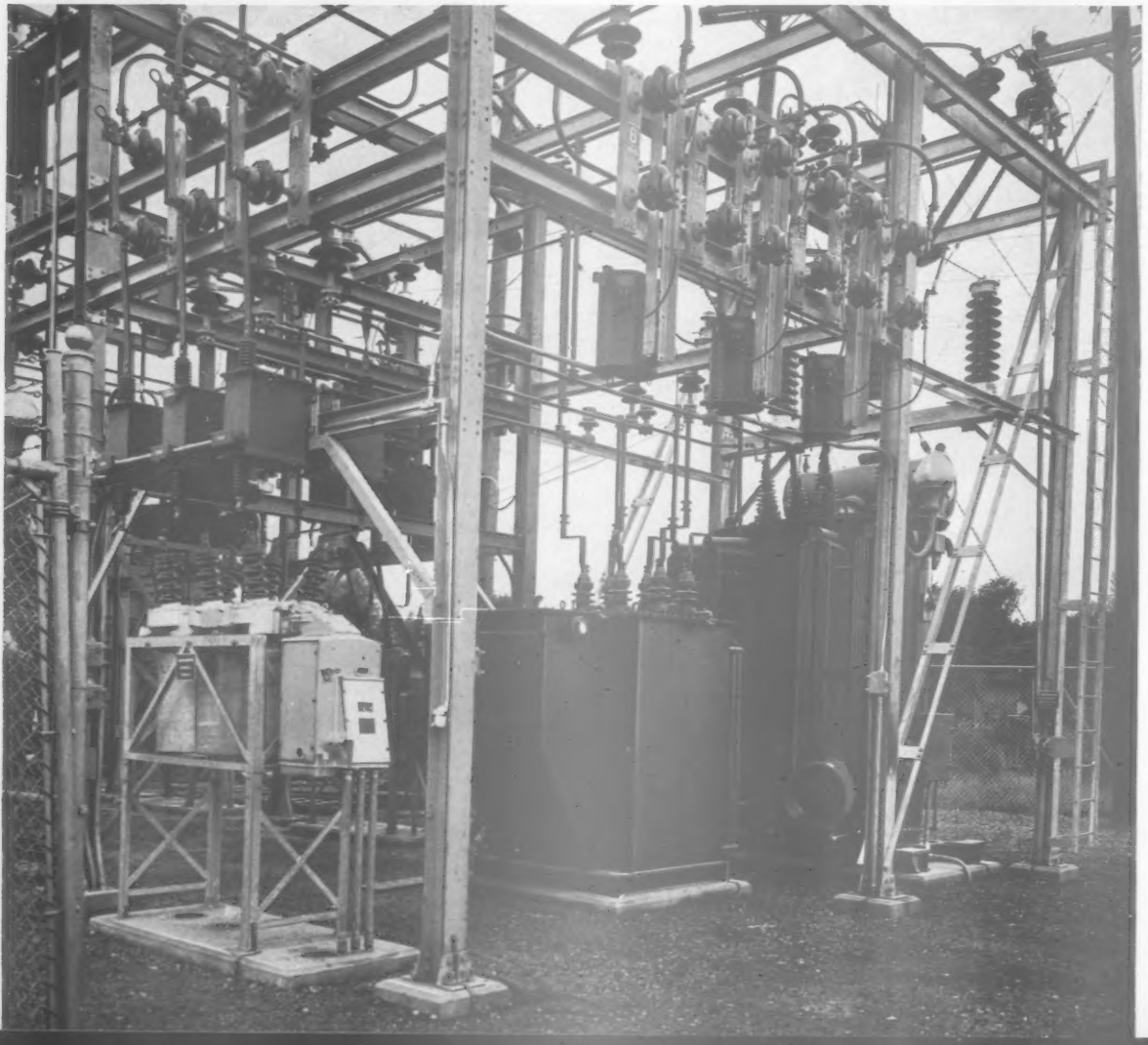
Because of these differences, two methods of rating have been adopted, one for each group of transformers.

In the first or H group, the performance is specified on the basis of a standard percent ratio error (10 or 2.5) which will not be exceeded with certain relaying burdens at from 5 to 20 times rated secondary current. Specifications are also for maximum secondary terminal voltages at which the specified ratio errors will not be exceeded, when using certain standard relaying burdens over this same range of currents. Likewise, the relaying burdens at which the limiting ratio errors will not be exceeded in the range of from 1 to 5 times rated secondary current are specified, in ohms. (Rated secondary current is 5 amperes unless otherwise specified.)

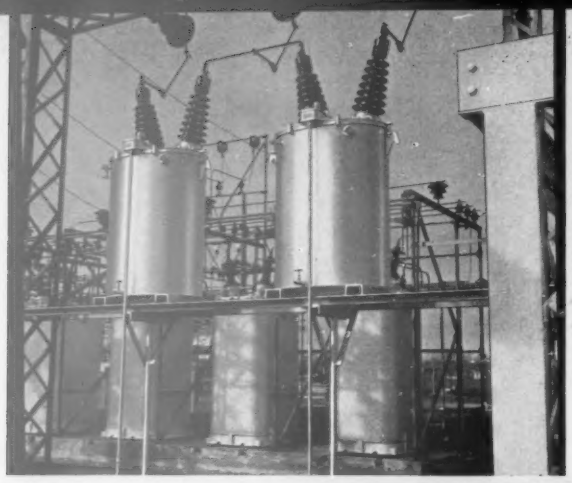
The standard designations are 10H50, 2.5H800, etc. The class 10H50 means that 10 percent ratio error will not be exceeded at secondary currents of from 5 to 20 times rated current with standard relaying burdens such that secondary terminal voltages greater than 50 volts will not be required, and also that this same ratio error will not be exceeded at secondary currents of from 1 to 5 times normal rating with relaying burdens up to and including 2 ohms. The class 2.5H800 can be similarly interpreted.

In the second or L group, the performance is specified on the basis of a standard percent ratio error (10 or 2.5) which will not be exceeded with certain standard relaying burdens at 20 times rated secondary current. The maximum secondary terminal voltage at which the specified ratio errors will not be exceeded when using certain standard relaying burdens at this same current value, as well as standard relaying burdens at which the limiting ratio errors will not be exceeded over the range of from 1 to 20 times rated secondary current, is specified.

The standard designations are 10L-200, 2.5L-400, etc. The class 10L-200 means that 10 percent ratio



IMPORTANT UNITS of this distribution system are three dry type current transformers (25-60 cycles, 200-5 amps, 15,000 volts) and 3 oil-filled potential transformers (200 va, 60 cycle, 14,400-120 volts).



POTENTIAL TRANSFORMERS in the foreground are oil-filled, 550 va, 60 cycle, 69,000-115 volt units. A. S. A. specifications thoroughly cover the characteristics of potential transformers.

error will not be exceeded at 20 times rated secondary current with standard relaying burdens such as to require secondary terminal voltage of not over 200 volts. (At 5 amperes rated secondary current, 20 times rating or 100 amps and standard burden B-2 would require a terminal voltage of 200 volts.) Also, this same error of 10 percent will not be exceeded with secondary currents of from 1 to 20 times rating and a standard relaying burden B-2. The class 2.5L-400 has a similar meaning.

Phase angles of current transformers under relaying conditions have not been specified, since, in general, transformers with ratio errors classified as specified would have relatively small phase angles of no particular significance in most relay application.

While this method of accuracy classification seems somewhat complicated and results in a multiplicity of classes, it seems that it should be effective and rather definitely describe a current transformer's limitations. It also seems to be about as simple as possible for the present.

Nameplate data

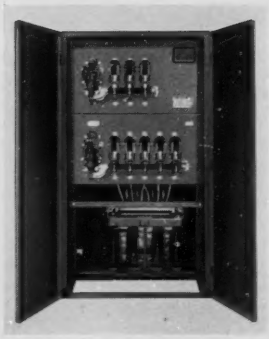
Section 4.075 (a) for current transformers (except bushing types) substitutes rated insulation class for maximum circuit voltage rating, in order to more clearly show the insulation values and, therefore, the voltages on which the transformers may be used. A "data sheet" number is to be shown and such data sheets are to be available and show such information as accuracy classification, thermal and mechanical limits and other information of general use.

In (b), a rated insulation class, added to the ratio requirement expressed in rated primary and secondary voltages, identifies a potential transformer more completely. The "data sheet" requirement has also been added. Group (c) has been added but no requirements have as yet been set up.

Standardization efforts continue

While part 4 of A.S.A. C57.1-1942 is now an American Standard, the committees which functioned to bring about the revision of the former proposals have been continued primarily for the purpose of completing those sections at present not completed. They are now considering the industry's criticisms which may affect possible future revisions of the standards.

New Magnetic, Reduced Voltage Cage Motor Starter

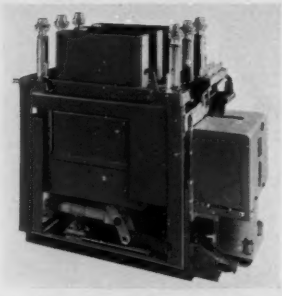


A new magnetic, reduced voltage cage motor starter — announced as type "ARC" — protects motors from sustained overloads, locked rotor condition, single-phasing and overloading from too frequent starting. This is accomplished with an accurately calibrated, thermal overload relay. Built for general industrial applications, the new starter is now available for control of motors from 5 to 2,500 horsepower, up to 5,000 volts, 3-phase, 50 or 60 cycles.

Reduced voltage, two-point starting is obtained with a built-in auto-transformer, utilizing accurate, synchronous motor driven, adjustable timing relay for transition from starting to running position. (Units rated through 800 hp have built-in auto-transformers; above 800 hp, auto-transformers are furnished for separate mounting.)

Interrupting capacity rating of the new starter is ten times the motor's full load current. Type "ARC" starters like the 200 hp, 440-volt, 3-phase, 60-cycle unit illustrated are designed for low cost, yet will withstand severest operating duty.

New "Ruptair" Breaker for 5,000 Volt Oil-less Switchgear



Following the trend toward oil elimination in indoor switchgear equipment, a new "Ruptair" magnetic type air circuit breaker has been developed and is now available in high voltage, oil-less switchgear rated 5,000 volts and below and 150,000 kva interrupting capacity and below. The "Ruptair" breaker has overall dimensions as compact as standard oil breaker switchgear, with all parts readily accessible.

Illustrated is a new air breaker for use in vertical lift metal-clad equipment. The arc chute has been carefully coordinated with the contact and arc runner design to give consistent and reliable interruption through the entire range of current to be interrupted.

For further, more detailed information regarding these new products, write the Editors of ELECTRICAL REVIEW.

SCALE MODELS INTRODUCE VISUAL PLANNING OF UNIT SUBSTATIONS

Components of electrical distribution substations are cut down to size, too, with the new models . . . and complete layouts can be assembled in a few minutes.

John McGuire

MIXED APPARATUS DIVISION • ALLIS-CHALMERS MANUFACTURING CO.

New scale models of substation equipment are enabling engineers to design industrial load center unit substations faster and more easily than has been possible in the past. With these models, an engineer planning an installation can experiment with various possible arrangements of equipment and quickly *see* which one best fits his electrical and space requirements.

Standardization of design has enabled the manufacturer to predict dimensions of equipment. Thus, accurate scale models can be made. The need for these models has arisen because of the rapid spread of the load center distribution system. Virtually every new plant of any size has used a load center distribution system. This means bringing the primary voltage, which may be from 2400 to 13,200 volts, right to the center of load. Now the stepdown substation of the plant will not be located in some convenient spot outdoors, nor hidden behind a building. It will be right in the center of the production area. Here space is money.

The engineer planning an industrial distribution system must use as little as possible of the manufacturing area for his substation. The load center unit substation, being not only compact but also safe and attractive in appearance, has met the requirements of an industrial substation.

Important space considerations

But, a compact substation is not enough to insure efficient use of vital floor space. The installation of the substation must be planned so that adequate floor space is provided but not wasted. Little or nothing is gained by providing excessive space around a load center unit substation. Realizing this, engineers have taken great pains to insure against wasted space. On the other hand, many installations have but little space available for the substation. This is particularly true in the modernization of existing factories.

In either case, the engineer planning the power distribution system must make dozens of sketches and layouts to select his substation area. In this work the models are a valuable tool. Using them, the engineer sets up the various combinations of equipment that he has in mind. Since all standard equipment is available in model form he is not restricted in his planning. As he completes each model arrangement he "sees" the actual installation. If the models are assembled on a sketch of the factory made to the same scale as the models, the relative dimensions are apparent at once. The effect of possible future expansions can be checked without difficulty.

Equally important, the engineer has a visual "preview" of the final installation. Because of the stress on good appearance, the engineer dare not ignore the display side of the substation. Being inside the plant, the substation is seen daily by workers and visitors. This factor is so important that models have been made on individual projects for no other purpose than to arrive at the most pleasing design.

Models convey engineer's ideas

Then, too, after a substation is designed the engineer often has to sell his ideas to other men. They may be men in his company or it may be customers. These men may have little knowledge of technical equipment; yet the engineer must make it clear to them just what he plans to do. It is difficult, if not impossible, to do this with no more than words, a single line diagram and sketches. By using models the equipment represented by a single line diagram can be visualized by everyone. The advantage of a particular arrangement is easily seen.

Load center unit substations have proved to be a means of improving industrial distribution systems, but their application has required more careful engineering than previous types of substations. Scale models have simplified this application work by enabling the users of load center units to plan their substations visually. The simplicity of this planning is illustrated by the following series of photographs.

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PLANNING A LOAD CENTER SUBSTATION installation with the new unit substation models, an engineer has before him accurate reproductions of all of the standard component parts he might possibly include in his layout. Guided by a "Check-list," he can easily compare relative sizes and floor space requirements of equipment.

SELECTING THE PROPER TRANSFORMER is his first problem. By checking his load he can calculate the proper transformer rating. Primary voltage is determined by his power supply; secondary voltage by his load. From available oil or Chlorextol liquid filled and dry type transformers, he selects a 1000 kva dry-type unit.

SELECTING PROPER HIGH VOLTAGE SWITCHING equipment for the substation is the next problem. As the models show at a glance, he has a large variety of equipment available. He selects vertical lift metal-clad switchgear for the greatest protection and flexibility. He also uses a drop collar throat to simplify connection of the transformer and the switchgear in the substation he is planning.

WITH A SPECIAL SLIDE RULE designed to calculate secondary short circuit current, the engineer determines the proper size low voltage breakers to use. By checking his load, he determines the number of feeder breakers necessary. Here he starts building up his low voltage switchgear, using first the bus transition unit, then a section of three 50,000 mp. I. C. manually operated air circuit breakers.

THE COMPLETED MODEL UNIT SUBSTATION is easy to check for final space requirements. By sketching a section of this plant to the same scale as the models on the cross-section paper as shown, he immediately determines that the unit substation will fit into the space available. In front of the unit will be one of the aisles in the plant.

NOW, OTHER MEN CAN SEE the model unit substation the engineer has planned. Completed, the unit consists of an incoming line breaker with an auxiliary compartment for housing control power and potential transformers, a 1000-kva dry-type transformer, a low voltage bus transition unit, and nine 50,000-ampere feeder breakers.

TAKING STOCK OF STORED ENERGY IN MAGNETIC CIRCUITS

With a d-c contactor, is the interruption of coil current more difficult with the contactor open or closed? Take a guess . . . then reason it out.

Walther Richter

ENGINEERING DEVELOPMENT DEPT. • ALLIS-CHALMERS MANUFACTURING CO.

To build up a magnetic field, energy must be furnished; this energy then resides in the medium in which the magnetic field exists. When the field disappears, all or part of this energy is available again and may be converted into other forms of energy.

There are several ways of expressing the amount of energy stored in a magnetic field. One of them is the relation well known to electrical engineers:

$$W = \frac{1}{2} Li^2 \text{ wattseconds or Joules} \quad \ldots\ldots\ldots\ldots (1)$$

In this presentation the energy is expressed as a function of the inductance of the device and the current flowing through it. Another method of giving the magnetic energy is by the relation

$$W = \frac{V}{4\pi} \int_0^B HdB \text{ ergs} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

V is the volume of the space in which the field exists, in cubic centimeters, while H and B are the magnetic field strength in Oersteds and magnetic induction in Gausses, respectively. (10^7 ergs are equal to one Joule.)

It would seem that with the existence of these relations the question of magnetic energy is all settled. Nevertheless, in practice there are quite often conditions which do not conform easily to one or the other method of approach. Some of the fundamentals underlying this problem might be pointed out.

Concept of true inductance

For the application of equation (1) we must know the value of L, the inductance. The unit of the inductance is the Henry, and a coil is said to have an inductance of, let us say, two Henry if a voltage of two volts appears across it, as long as the current through it is changing at the rate of one ampere per second. A true inductance would have to be considered without resistance, which of course is a case that cannot be realized in practice.

However, the concept of a true, resistanceless inductance is of such great help in the visualization of magnetic problems that it should become well established in the mind of the electrical engineer. No voltage would exist across such a true inductance as soon as the current ceases to *change* (compare this with the behavior of an ohmic resistance where the current must cease to *exist* in order to have zero voltage across the resistance). When the current ceases to change through an inductance, the magnetic field associated with it remains at a constant value; since, as just explained, the voltage across the inductance will then be zero, electric power is no longer furnished for the maintenance of the magnetic field.

From this simple analysis it is at once evident that electric power must be expended only during the building up of the magnetic field. However, maintenance of the field does not require power. Off hand, this seems to be contradicted by the fact that power is expended in the field excitation of a-c or d-c machines, but it must be remembered that this expenditure is only due to the unfortunate fact that we do not have a conductor material with zero resistance. If we could replace all field coils overnight with a material having a resistance 100 times less than that of copper, then the maintenance of the magnetic fields in our electrical machines would at once require the expenditure of only one percent of the power that they take now.*

In the preceding paragraph the term inductance was defined. It may also be regarded as the flux linkage at one ampere divided by 10^8. The equivalence of the two definitions is very easily seen as follows: the voltage induced in a coil can be stated in two ways:

$$e = L \frac{di}{dt} \text{ volts} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$e = n \frac{d\phi}{dt} \times 10^{-8} \text{ volts} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

From these two equations it is obvious that:

$$L\ di = n\ d\phi \times 10^{-8} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

From which follows:

$$L = n \frac{d\phi}{di} \times 10^{-8} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

AT LEFT: Undercutting the mica between copper segments on commutators is a highly important step in construction. A rotating blade cuts out full width of mica, leaves no mica on sides to cause poor commutation. Similar undercutting should be done in proper commutator maintenance.

*Note: The reader is invited to consider what happens to the L/R ratio, i.e., the time constant, if this reasoning is carried to the limit of R = 0. Perhaps we would not be able to build up the magnetic field at all. Or would we?

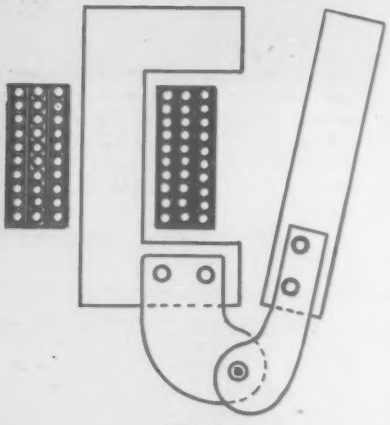


Fig. 1

If there is proportionality between flux and current, the value $n \times \frac{d\phi}{di}$ can be replaced by $n \times \frac{\phi}{i}$, proving the definition of the inductance as the flux linkage at one ampere; that is, the flux existing due to a current of one ampere multiplied by the number of turns with which it links, and divided by 10^8.

Iron upsets formulas

All this is very simple and logical as long as proportionality exists between the magnetic flux and the current exciting it, and as long as all the flux can be considered as linking with all the turns. Due to the use of iron in practically all magnetic structures, however, the condition of proportionality is not fulfilled, and the application of the above formulas and any conclusions drawn with them as a basis may lead to considerable error.

Take for instance the simple case of a magnetic structure such as found in a contactor, as shown in Figure 1. Suppose that we are dealing with a d-c contactor. When the magnetic structure is closed, the magnetic flux will certainly be larger than if we were to block the contactor structure in the open position. If we were asked, for which case the interruption of the coil current would more difficult, we would undoubtedly feel that it would be for the closed position, where we obviously have a higher inductance (since the flux linkage for one ampere is certainly higher). Since we are dealing with direct current, the coil current is the same in both cases. An experiment will show, however, that interruption is more difficult for the open position, indicating that the energy that must be dissipated is larger in the case of the structure being blocked in the open position than when it is closed, and our equation (1) seems to be giving an erroneous result.

When the magnetic circuit contains iron and the current rises to a value causing saturation of the iron parts, the definition of the inductance becomes rather difficult. According to equation (3), the voltage induced is proportional to the rate of change of current, and the proportionality factor is the inductance. Now, if saturation takes place in some part of the magnetic circuit, the magnetic flux will not change linearly with the current, and since the induced voltage is due to the changing magnetic flux, a current changing linearly with time will not produce a constant voltage any more, as would be indicated by equation (3). In other words, the value of the inductance is changing while the current is building up. Under these circumstances, we cannot expect to obtain correct results for the stored energy calculated from equation (1), since the value of the inductance is not constant.

Magnetic energy measured

Suppose that the magnetic characteristic of the iron structure alone is given by curve A, as indicated in Figure 2, while the magnetic characteristic of the air gap in the open position is given by the straight line B. In the closed position the magnetic characteristic of the device would then simply be curve A (assuming a zero gap at the joints), while for the open position we would have to combine the two characteristics in the well known manner by adding the abscissae of the two characteristics for any given ordinate as shown for one point in Figure 2. This results in curve C. Suppose that the current of the exciting coil at rated voltage is given by the abscissa OP. In the open position the flux would be given by the ordinate ϕ_1, while in the closed position the flux is increased to the value ϕ_2, which is seen to be considerably larger than ϕ_1.

In order to arrive at the magnetic energy stored in these two cases, it is extremely helpful to visualize the excitation coil again with zero resistance. Now assume that we bring up the excitation from zero ampere to the value given by the abscissa OP at a uniform rate. Such a result could be fairly easily obtained by feeding the coil over a variable resistance from a reasonably high voltage so that the current would be essentially determined by the series resistance only. We then could vary this resistance in such a way that the current would rise at a uniform rate to the desired value. If we now place a voltmeter across the coil, then a voltage will be existing across the coil only during the time that we are changing the current. The wattage at every instant will be given by the instantaneous values of voltage and current, and the average of the wattage values multiplied with the total time of the change will give us the amount of energy delivered to the coil; since the coil resistance was assumed as zero, this energy must then be residing in the magnetic field.

It is seen that for the closed position (curve A) the flux rises rapidly during the first part of this period, which will mean that the voltage appearing across the coil will be high; during the later stages, that is, after the flux has gone through the knee of the curve, the flux will change at a slower rate with the increasing current, and the voltage across the coil will therefore be low. The wattage will consequently be rather small, since at the time when the voltage is high the current is still low, while when the current has reached a large value the voltage will be low. For the open condition of the magnetic structure, on the other hand, the flux, while not reaching as high a value as for the closed condition, rises more linearly so that the voltage appearing across the coil will be essentially of constant value during the whole period of changing current. It becomes apparent that under certain conditions the magnetic energy may be higher in the open condition of the magnetic structure than in the closed one.

Quantitative study expanded

To obtain a more quantitative insight into the conditions just outlined, consider the small current change di in Figure 2. The average value of current existing during the time interval dt in which the current change di is taking place is i_1. The change in flux produced by the change di is given by the value $d\phi$. The voltage which exists across the coil during the interval dt will therefore be given by:

$$e_1 = n \frac{d\phi}{dt} \times 10^{-8} \text{ volts} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

The instantaneous wattage is given by the product $i_1 \times e_1$, or

$$P_1 = e_1 i_1 = n i_1 \frac{d\phi}{dt} \times 10^{-8} \text{ watts} \quad \ldots\ldots\ldots\ldots\ldots (8)$$

The energy delivered to the coil during this time will be

$$P_1 \, dt = n i_1 \, d\phi \times 10^{-8} \text{ wattsecs.} \quad \ldots\ldots\ldots\ldots\ldots (9)$$

The amount of energy delivered during the time dt is consequently n times the cross hatched area in the figure (with due regard to the scales for i and ϕ, of course) times 10^{-8}, a relation which has been pointed out in most textbooks on magnetic circuits. The total energy delivered to the magnetic circuit is therefore proportional to the area enclosed between the ordinate axis and the magnetization curve of a device. Figure 3A shows this area crosshatched for the closed position of the magnetic circuit, while Figure 3B shows it for the open condition of the magnetic structure. It is seen that, depending on the sharpness of the knee of the magnetization curve and the amount of exciting current, the energy may be very much smaller in the case of the closed circuit than in the case of the open circuit, even though the end value of the flux in the closed condition is considerably larger than the one in the open condition.

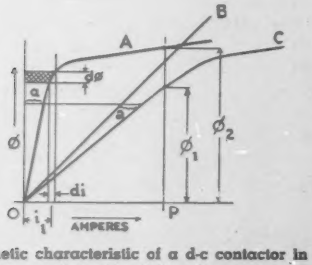


Fig. 2 — Magnetic characteristic of a d-c contactor in closed position is represented by A, of the air gap in open position by B, and of the device in open position by C. Crosshatched area times n is energy delivered during time dt.

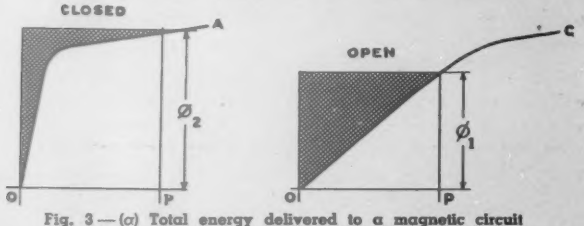


Fig. 3 — (a) Total energy delivered to a magnetic circuit in closed position is shown by cross-hatched area. (b) Total energy when circuit is open.

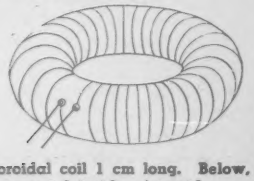
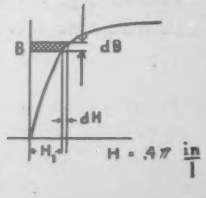


Fig. 4 — (a) Toroidal coil 1 cm long. Below, (b) is the H-B curve of core material inside of toroid.



Appendix

Equation (2) can easily be derived by using the same reasoning that led to the development of equations (7), (8), and (9). Consider a toroidal coil as shown in Figure 4A with a mean length of 1 cm and a cross sectional area of A cm^2. Let the number of turns be n. Suppose that the inside of the toroid is filled with a magnetic material the characteristic of which is given by the H-B curve, Figure 4B. According to definition,

$$H = .4\pi \frac{i \times n}{l} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

and

$$\phi = B \times A \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

Suppose that we increase the current through the coil from zero to a value i. During this time the magnetic field strength H will increase proportionally to i as given by equation (10). The magnetization curve will give us the value of B and therefore the value of the flux belonging to every value of the current i. Consider the instant when H has reached the value H_1. The current at this instant is obtained by solving equation (10) for i, which leads to

$$i = \frac{Hl}{.4\pi n} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10a)$$

When the current changes an amount di during the time interval dt, H will increase a corresponding amount dH. The flux will increase by an amount A × dB. The induced voltage during the time interval dt will therefore be

$$e = n A \frac{dB}{dt} \times 10^{-8} \text{ volts} \quad \ldots\ldots\ldots\ldots\ldots\ldots (12)$$

and the energy delivered to the magnetic circuit during this interval will be equal to the wattage times the time interval dt, that is,

$$dW = e \, i \, dt = \frac{n A \, dB \, H \, 1}{.4\pi n} \times 10^{-8} \text{ wattsec.}$$

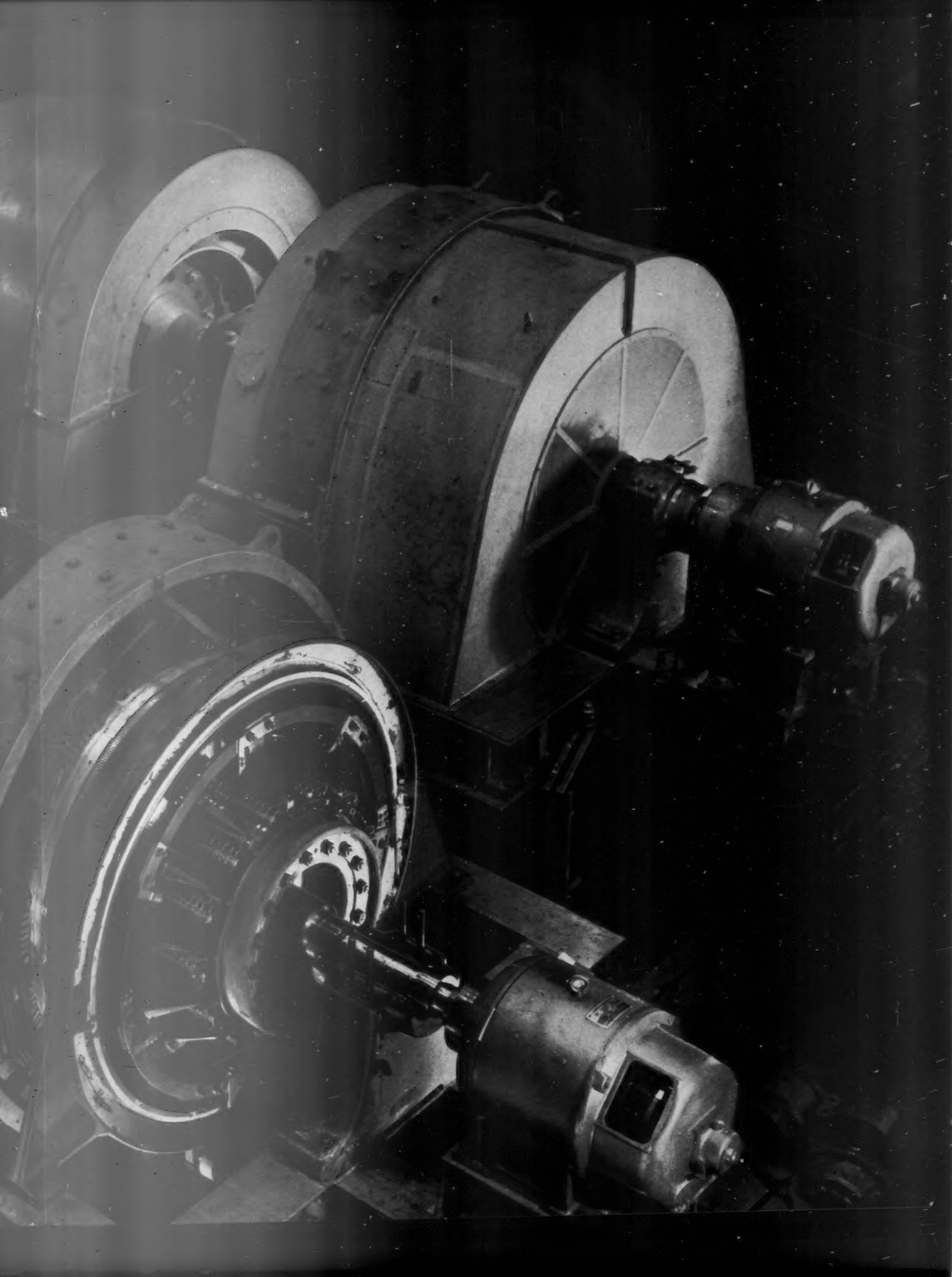
$$= \frac{A \, 1}{.4\pi} H \, dB \times 10^{-8} \quad \ldots\ldots (13)$$

H × db is equal to the small crosshatched area in Figure 4. Since A × 1 equals the volume of the magnetic material, the total energy delivered to the magnetic circuit is equal to

$$W = \frac{V}{4\pi} \int_0^H H dB \times 10^{-7} \text{ wattseconds} \quad \ldots\ldots\ldots (14)$$

Since one wattsecond is equal to 10^7 ergs, the identity of equations (2) and (14) is evident.

ON FOLLOWING PAGES: Two 5000 kw synchronous motor-generator sets are arranged for final checking on the electrical test floor. Tests completed, unit in the back has its motor and generators covered to complete the assembly, after which it will be disassembled for shipment. Motors are rated 7000 hp, 514 rpm, .8 power factor, 13,200 volts; each generator, 2500 kw, 700 volts; each set provided with one 45 kw and one 25 kw, 250 volt exciter.



ECONOMICS OF ELECTRIC POWER PUMPING

Motor-driven centrifugal pumps are being applied to more and more pumping jobs. With a number of possible combinations available, careful consideration should be given to make sure the most economical arrangement is selected.

C. A. Richardson

CENTRIFUGAL PUMP DEPARTMENT • ALLIS-CHALMERS MANUFACTURING COMPANY

The well engineered water works plant must provide for a wide range in capacity to meet both the minimum and peak demands. In the early stages of water works development, pumping engines were almost universally used and the necessity of operating over a wide range in conditions did not present any particular problems. Now that motor driven centrifugal pumps are rapidly displacing other types of pumping equipment, the problem of variable demand requires careful consideration to make sure that the most economical arrangement is provided.

The most common methods of providing for variable demand are:

1. Elevated storage tanks
2. Multiplicity of varying capacity pumping units operating in parallel
3. Steam turbine driven units
4. Throttling
5. Variable speed electrical motors
6. Constant speed electrical motors with variable speed couplings

The factors that enter into the selection of the proper type of drive for an economic installation are many. In this discussion remarks are limited to the methods of throttling, variable speed electrical motors, and constant speed motors with variable speed couplings.

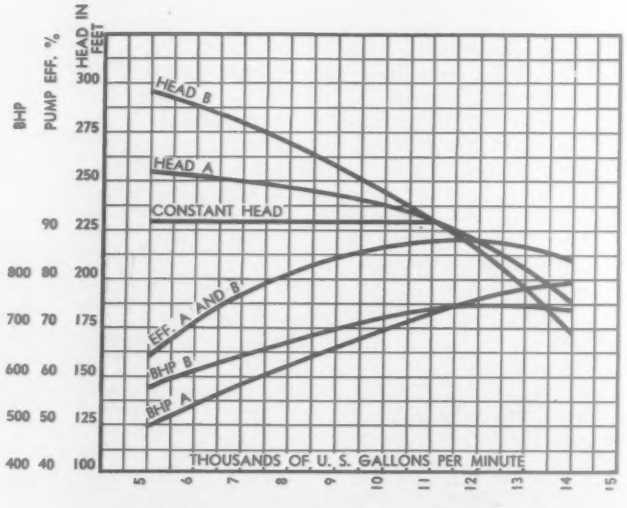


Fig. 1 — Characteristics of 16 mgd, 230 foot head, single stage centrifugal pump at 900 rpm.

Throttling for variable demand

When centrifugal pumps are operated against or near constant discharge pressure for variable capacity demands at constant speed, this is in effect throttling, whether or not there has been a change in discharge valve setting. Under these conditions the slope of the characteristic curve should be carefully considered to make sure that the characteristics are best for desired operating conditions, and under these conditions a flat head curve is desirable. If the pump is discharging against a wide variation in discharge head, a steep head curve is preferable.

The head capacity curves A and B, Fig. 1, illustrate the difference in centrifugal pump performance for head curves with comparatively flat and steep characteristics. Should one of two centrifugal pumps (with characteristics as shown by curves A and B) be considered for operating over a wide range in capacity against constant or reduced heads at constant speed, then it is obvious that the flat head curve is preferable. If the pumps are to operate against a wide variation in discharge pressure, a steep head curve is preferable.

Table 1 gives comparative data for constant and variable speed for constant discharge pressure operating conditions. This tabulation shows that a flat head characteristic (Curve A, Fig. 1) has the advantage for devices where motor slip losses are proportional to the reduction in speed. This is due to the fact that the speed reduction required to meet a specific condition is less for a flat head curve than for a steep head curve. The effect of slip losses for increased speed reduction will be partially offset by increased pump efficiency, provided that the corresponding point for constant speed is back of the best point of efficiency; for example, at the 52 percent capacity, 230 ft constant head point, the pump efficiency is 72 percent for curve A and 74 percent for curve B. However, if the corresponding point at reduced speed is beyond the best point of efficiency on the normal speed curve, the pump efficiency will be less at reduced speeds.

For devices where the reduction in efficiency is not proportional to change in speed such as with a d-c motor, the steep head characteristic has the advan-

tage. This difference is due to increased pump efficiency.

Variable speed savings

From the data in Table 1, calculations show the following kw power saving is obtained for variable speed over constant speed at 52 percent capacity:

	Curve A	Curve B
Wound rotor induction motor...	24.6 kw	73. kw
D-c motor and rectifier.....	20.9 kw	99.5 kw
Synchronous motor and variable speed coupling.....	21.9 kw	91.8 kw

The kilowatt saving at other points can be similarly obtained. The value of these savings in dollars is dependent on savings for energy costs that can be made on an average yearly basis, and the capitalization of energy savings.

On installations requiring only 5 to 10 percent speed reductions, as illustrated above, the merits of the variable speed drive over the constant speed drive may be hard to justify, due to the greater initial cost. This question is one that should be carefully studied when new equipment is to be purchased.

However, on installations requiring upwards of 20 percent speed reduction, no mathematical contortions are necessary to justify the installation of variable speed equipment. It is more or less evident from the outset that a variable speed installation will pay dividends, provided that a good percentage of the operation is at considerably reduced conditions. Such an installation is illustrated on Fig. 2, covering two single stage pumps in series, rated 8 mgd against 382 feet total head, operating down to 4.15 mgd against 294 feet head.

The energy saving shown in Table 2 clearly indicates that some type of variable speed drive will pay dividends. The question here is what form of variable speed arrangement will prove most advantageous, and this will depend somewhat upon local conditions. Fig. 4 indicates the comparative energy savings for various arrangements.

Variable pitch v-belt drive

Curve E on Fig. 3 represents the energy input that would be obtained with a unity power factor, 1800 rpm synchronous motor, using variable pitch v-belt sheave, adjustable while in motion. This arrangement would be the most economical from an energy standpoint, provided such a variable speed drive of this magnitude were available in a commercial unit. However, drive would greatly exceed present day established limits in belt speed and sizes. The limitations in belt speed could be overcome by choosing a 1200 rpm motor and a pumping unit with a top speed of 1200 to 1400 rpm. The pump efficiency at 1200 rpm would be lower than at 1800 rpm. The synchronous motor at 1200 rpm would cost less than at 1800 rpm.

The overall width of the sheaves for such a drive would be approximately six feet. While no adjustable pitch diameter sheaves of this face width have been built, there is a possibility that such a drive could be designed in the future to meet these requirements satisfactorily.

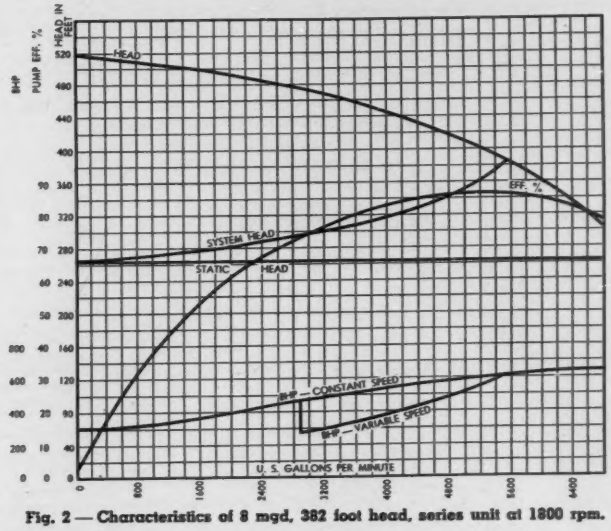


Fig. 2 — Characteristics of 8 mgd, 382 foot head, series unit at 1800 rpm.

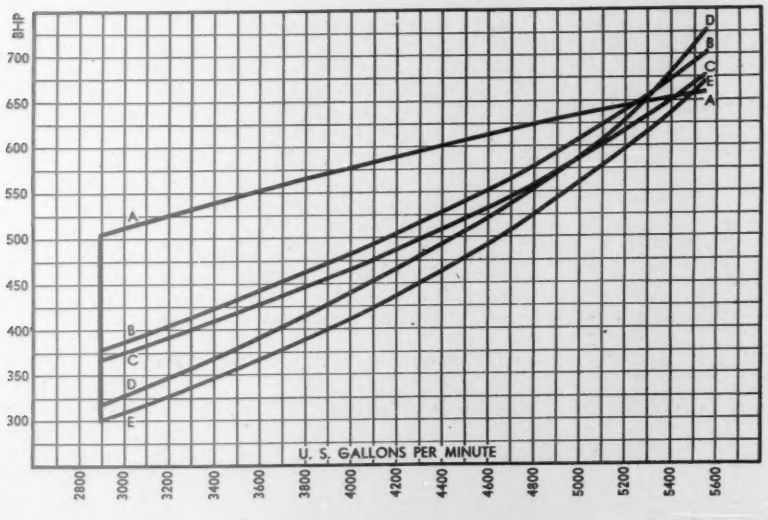


Fig. 3—Comparison—adjusting pump speed over throttling discharge. Curves — A: Horsepower input constant speed, throttling for reduced capacity; B: Horsepower input variable speed, synchronous motor hydraulic coupling both pumps; C: Horsepower input variable speed, wound rotor induction motor; D: Horsepower input variable speed, d-c motor and rectifier using shunt field control; E: Horsepower input variable speed, synchronous motor with variable speed, constant efficiency mechanical speed reducer.

TABLE I — DATA FOR CONSTANT AND VARIABLE SPEED FOR CONSTANT DISCHARGE PRESSURE

OPERATING CONDITIONS — Constant head (230 ft) at pumping station.	Capacity, percent		52.0	60.0	68.0	76.0	84.0	92.0	100.0
	Capacity, gpm		5770	6660	7550	8440	9330	10200	11100
	Head, feet		230	230	230	230	230	230	230
CONSTANT SPEED — Unity power factor, synchronous motor (approximate unit cost — $12,000†).	Pump disch., head ft	*A	253	251	248	245	242	237	230
		*B	291	283	275	265	254	243	230
	Electrical hp input	A	560	592	627	657	709	746	782
		B	642	666	694	708	743	764	782
	Comb. eff., percent	A	65.8	71.2	75.5	79.7	80.4	82.0	82.5
		B	66.2	71.5	75.7	79.9	80.5	82.1	82.5
	Kwh/mg	A	1209	1108	1032	967	948	908	877
		B	1380	1242	1142	1042	992	930	877
VARIABLE SPEED — Constant head, wound rotor induction motor with secondary control (approximate unit cost—$18,500).	Percent rpm	A	95.4	95.9	96.4	97.1	97.6	98.6	100.0
		B	89.7	91.1	92.6	94.2	95.9	97.7	100.0
	Electrical hp input	A	527	564	602	647	695	742	790
		B	544	582	629	663	705	750	790
	Comb. eff., percent	A	63.6	68.5	72.8	75.8	78.0	79.8	81.5
		B	61.6	66.4	69.8	73.9	77.0	79.0	81.5
	Kwh/mg	A	1138	1050	992	953	926	905	887
		B	1174	1088	1035	978	938	915	887
VARIABLE SPEED — Constant head, d-c motor and rectifier, using shunt field control (approximate unit cost—$35,000).	Ehp input to rectifier	A	532	573	618	670	724	781	844
		B	519	562	612	667	722	781	844
	Comb. eff., percent	A	63.0	67.5	71.0	73.2	75.0	75.9	76.4
		B	64.5	68.7	71.8	73.5	75.2	75.9	76.4
	Kwh/mg	A	1149	1070	1020	987	964	952	946
		B	1120	1052	1008	983	961	952	946
VARIABLE SPEED — Constant head, sychronous motor with variable speed coupling (approximate unit cost — $18,000).	Percent rpm	A	92.8	93.2	93.7	94.2	94.8	95.8	97.2
		B	87.2	88.6	90.0	91.6	93.2	95.0	97.2
	Electrical hp input	A	544	582	623	672	720	764	812
		B	564	602	640	687	729	772	812
	Comb. eff., percent	A	61.5	66.4	70.4	73.1	75.3	77.6	79.4
		B	59.3	64.2	68.4	71.4	74.3	76.8	79.4
	Kwh/mg	A	1175	1090	1028	989	960	932	910
		B	1220	1128	1058	1013	974	941	910

*Curves A and B, Fig. 1

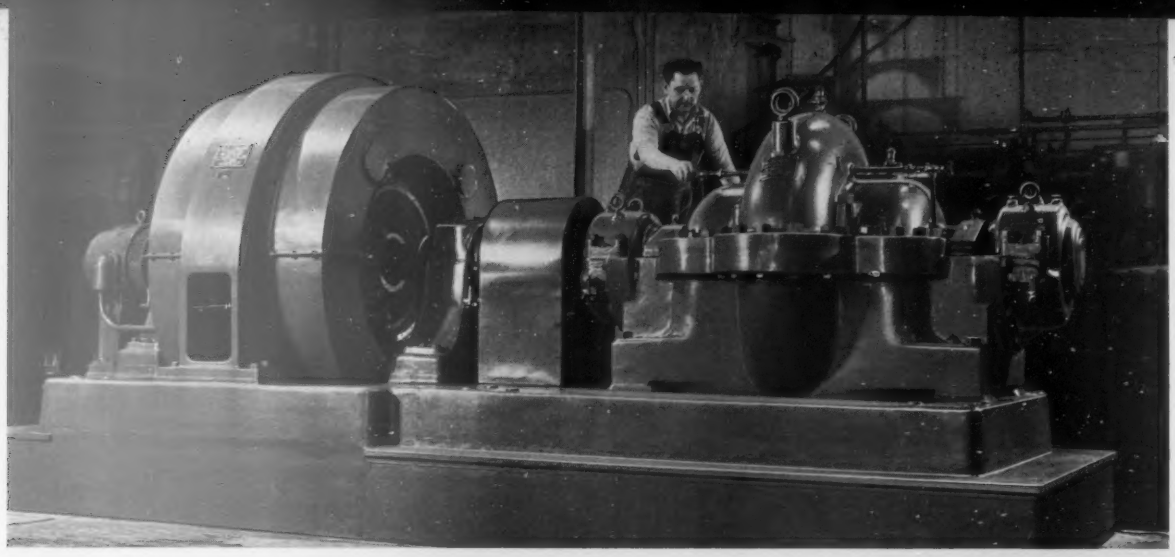
Comparative data on 16 mgd, 230 ft hd centrifugal pump unit operating at 900 rpm, with control.

† Approximate prices given for the various arrangements include: Pump, base and coupling; Motor—synchronous (unity power factor), induction (wound rotor), direct-current (600 volt); Starter (reduced voltage); Variable speed coupling (standard commercial unit); Power supply—a-c, 2300 volt, three-phase, 60-cycle.

TABLE II — DATA FOR CONSTANT AND VARIABLE SPEED FOR VARIABLE DISCHARGE PRESSURE

OPERATING CONDITIONS — Variable head at pumping station.	Capacity, percent	52.0	60.0	68.0	76.0	84.0	92.0	100.0
	Capacity, gpm	2890	3340	3780	4225	4670	5116	5560
	Head, feet	294	302	312	323	336	356	382
CONSTANT SPEED — Unity power factor, synchronous motor (approximate unit cost — $11,000).	Pump disch., hd ft	474	464	451	438	420	402	382
	Electrical hp input	503	538	564	594	618	638	659
	Comb. eff., percent	69.0	72.8	76.2	79.8	80.2	81.3	81.3
	Kwh/mg	2160	2005	1860	1725	1647	1550	1478
VARIABLE SPEED — Wound rotor induction motor with secondary control (approximate unit cost — $15,000).	Percent rpm	80.5	82.5	85.2	88.2	91.3	94.5	100.0
	Electrical hp input	367	404	448	493	543	606	666
	Comb. eff., percent	58.5	63.1	66.5	70.3	73.0	75.8	80.5
	Kwh/mg	1580	1505	1473	1445	1447	1485	1492
VARIABLE SPEED — DC motor and rectifier using shunt field control (approximate unit cost — $31,000).	Electrical hp input	319	364	417	471	534	614	727
	Comb. eff., percent	67.3	70.1	71.6	73.2	74.2	74.8	75.7
	Kwh/mg	1372	1355	1370	1389	1425	1495	1585
VARIABLE SPEED — Synchronous motor, variable speed coupling (approximate unit cost — $16,000).	Percent rpm	78.4	80.2	82.8	85.7	88.7	91.9	97.2
	Electrical hp input	378	420	463	509	564	626	703
	Comb. eff., percent	56.8	60.7	64.4	67.6	70.4	73.5	78.2
	Kwh/mg	1625	1563	1522	1505	1501	1522	1535
VARIABLE SPEED — Synchronous motor; variable speed coupling on one pump, other pump constant speed (approx. unit cost—$14,000). See figure 3.	Percent rpm, one pump	52.5	58.8	65.8	72.9	80.0	88.6	97.25
	Electrical hp input	359	400	450	493	545	605	673
	Comb. eff., percent	59.7	63.7	66.2	69.8	72.7	76.0	79.7
	Kwh/mg	1548	1490	1482	1457	1450	1474	1505

Comparative data on 8 mgd, 382 ft hd, series centrifugal pump unit at 1800 rpm, with control.



FOR THIS BOOSTER APPLICATION, this synchronous motor driven, constant speed pumping unit is a satisfactory combination. In a booster station it builds up reserves at regular intervals for peak loads to follow. It is rated 30 million gallons per day at 250 foot head, 500 horsepower.

With the two sheaves having adjustable pitch diameters and operated together, a speed reduction of 25 percent is obtainable. The center distance would not change, but it would be necessary to provide for adjustment to allow for stretch in the belts. The center distance would be approximately 65 inches.

While water works engineers naturally prefer the direct connected unit, the adjustable sheave drive has merit. The efficiency of the drive would be 98 percent, and this 98 percent efficiency would be maintained over the entire range in speed. The energy economy of this arrangement should be of interest to the water works engineer, particularly on smaller variable speed installations having high energy rates. The initial cost of this arrangement probably would not greatly exceed other types of variable speed arrangements.

Direct current motor drive

Curve D on Fig. 3 is the alternating-current energy input to a mercury arc rectifier with direct-current, shunt field control motor. This standard commercial arrangement is the most efficient of those listed in Table 2 for speeds below 92 percent normal as compared to the wound rotor induction motor, and for speeds below 97 percent normal as compared to the synchronous motor with variable speed coupling. The efficiency of the d-c motor is slightly lower than the unity power factor synchronous motor.

The efficiency of the rectifier is practically constant for constant d-c voltage output. In other words, if the output d-c voltage of the rectifier is held constant, an efficiency of approximately 94 percent will be maintained for wide variation in load.

The power factor on the a-c side of the rectifier will be approximately 93 percent for constant output d-c voltage. If the output voltage is reduced for speed control on the d-c motor, then the power factor will vary approximately in proportion to the reduction in d-c voltage.

The efficiency of a d-c motor with shunt field control will vary with reduction in speed and load. For the minimum condition of 80 percent normal speed, and approximately 40 percent normal load given in Table 2, the change in d-c motor efficiency is approximately 5 percent reduction, as compared to full load and normal speed. If the commutator voltage on d-c motor is reduced 20 percent to obtain the 20 percent reduction in speed, there is a greater drop in d-c motor efficiency, and for these conditions the change in d-c motor efficiency will be approximately 10 percent as compared to full load and normal speed. This makes it desirable to use shunt field control for speed variation when operating conditions permit.

The initial cost of this arrangement is somewhat greater than the other methods of providing for variable speed. This is due to the necessity of converting from a-c to d-c current. Where d-c current is available the d-c motor provides the most efficient method for variable speed. The cost of the d-c motor with shunt field speed control will be greater than for voltage speed control. The speed on the shunt field d-c motor is increased by weakening the field, whereas with voltage speed control the speed is reduced by reducing the voltage. In this case a 700 horsepower, 1400 rpm d-c motor is required for shunt field speed control, and a 700 horsepower, 1750 rpm d-c motor is required for voltage speed control.

This arrangement provides infinite speed points, and the speed can be set at any desired operating condition and it will remain constant even though there is a change in pump condition. The merits of this arrangement are more pronounced the greater the speed reduction required, and the margin in initial cost will be less the larger the unit.

Wound rotor motor drive

Curve C on Fig. 3 is the energy input to a wound rotor induction motor with secondary control. This is probably the most common of the variable speed drives, and its economy and cost is on a par with other arrangements. The reduction in efficiency for reduced speeds is proportional to the percent speed reduction, and the power factor will also drop. Standard commercial secondary controls above 500 horsepower have a maximum of seven steps with six speed points. In order to secure best results the reduced speed points must be carefully chosen. The wound rotor motor is sensitive to changes in voltage, frequency, and horsepower output, but slight changes in operating condi-

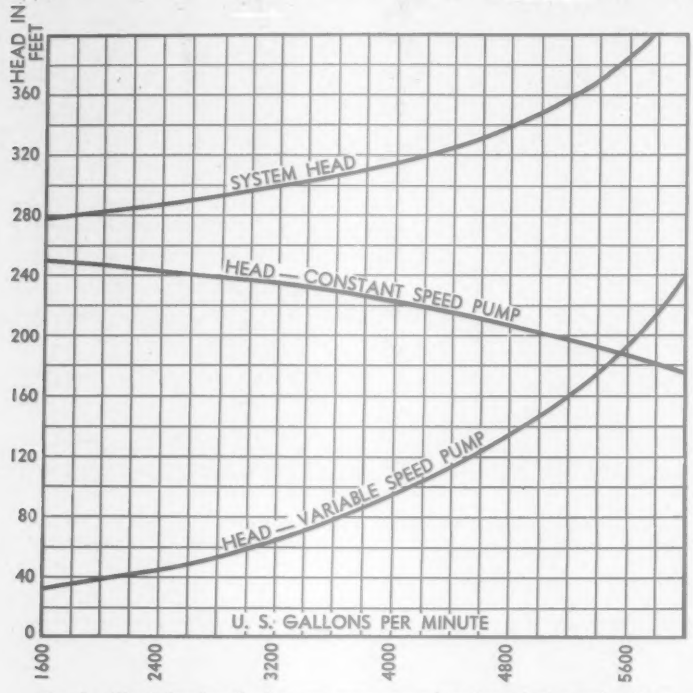


Fig. 4 — Head developed when one pump operates at constant speed and one pump at variable speed.

tions will not materially affect the overall economy of centrifugal pump operation, consequently the wound rotor induction motor gives a very satisfactory variable speed drive for centrifugal pumps. It probably is the simplest of variable speed arrangements.

Coupling-connected drive

Curve B on Fig. 3 is the energy input to a unity power factor synchronous motor with variable speed coupling connected between the motor and series pumps. The speed change affects both pumps equally. The efficiency of this arrangement is less than for the wound rotor induction motor. This is due to the initial efficiency loss at minimum slip in the coupling. The calculations for the tabulation are based on values using a hydraulic coupling. The economy of the magnetic coupling would compare favorably with the hydraulic coupling.

The magnetic coupling requires d-c current for excitation, which makes it necessary to furnish the synchronous motor with an oversize exciter, or the coupling may have its own excitation equipment.

Seven hundred horsepower is just about the maximum size of hydraulic coupling available at 1750 rpm. Larger sizes are available at lower speed, although standard commercial magnetic couplings are available in this size and larger.

The magnetic and hydraulic couplings offer infinite speed points for variable speed and are subject to the same performance factors as the wound rotor induction motor.

Fig. 4 shows the performance of a variable speed coupling connected between the two series pumps. One pump will operate at constant motor speed, while the other operates at variable speed. The efficiency of this arrangement is practically the same as for the wound rotor induction motor.

Since the greater part of the head to be developed by the variable speed pump is friction head, the pump will operate at constant maximum efficiency for all conditions shown in Table 2. This is the preferable arrangement using variable speed couplings and series pumps.

Synchronous motor drive

Curve A on Fig. 3 is the energy input to a unity power factor synchronous motor. The capacity variations are obtained by throttling. The head loss in the throttle valve to obtain the desired capacity is obtained by subtracting the corresponding system head from the corresponding pump head. For 52 percent capacity this head loss is 474 pump discharge head less 294 system head or 160 feet. The energy saving for the wound rotor induction motor as compared to throttling at this point is 100 kw, which on the basis of one cent per kilowatt hour is a saving of one dollar for every hour the unit is operated at this capacity. The saving at other points will be proportional to the operating point as compared to normal rating.

Inasmuch as most water works are required to provide for maximum demands and operate at somewhat reduced conditions most of the time, some provisions for variable demands should be made. From the above it is evident that when centrifugal pumping units are required to operate over a wide range in capacity at constant or reduced heads, some form of variable speed arrangement will pay dividends. Indications are that there may be many new types of variable speed drives available in the not too distant future.

AT RIGHT: One of the largest hydrogen-cooled turbine-generating units ever built, this recently installed machine is a later, more efficient version of "the world's most efficient," as the first 80,000 kw unit at Port Washington, Wisconsin, was known.

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A NEW VIEW OF CONVERSION FACTORS

Changing from one set of units to another can involve complicated formulas. But with this simplified point of view many engineering quantities can be transferred from one system to another with a simple operation.

W. C. Sealey

ENGINEER-IN-CHARGE • TRANSFORMER DESIGN • ALLIS-CHALMERS MFG. CO.

A conversion factor is simply the number by which a numerical value for a GIVEN unit must be multiplied to get the numerical value in terms of the REQUIRED unit.

The factor is equal to the number of REQUIRED units in one GIVEN unit.

For a complex term composed of several individual units, the change in each individual unit may be considered separately in calculating the conversion factor. The factor is equal to the number of REQUIRED individual units in one GIVEN individual unit if the individual unit is in the numerator, and the reciprocal of this if the individual unit is in the denomination. In other words, the number of REQUIRED individual units in one GIVEN unit is placed in the numerator of the factor if the individual unit is in the numerator; or in the denominator of the factor if the individual unit is in the denominator.

Example 1: To change 10 feet to inches, multiply by the factor 12 (the number of inches in one foot). Ten feet is equivalent to 10 x 12 = 120 inches.

Example 2: To change 120 ft per min to ft per sec, multiply by the factor 1/60 (the reciprocal of the number of seconds in one minute. Thus, 120 ft per min is equivalent to 120 x 1/60 = 2 ft per sec.

Example 3: To change 0.01 ft-lbs per sec per degree C to in-lbs per min per degree F, the conversion factor is obtained as follows:

The given unit is: $\frac{\text{ft} \times \text{lbs}}{\text{sec} \times {}^\circ\text{C}}$

The required unit is: $\frac{\text{in} \times \text{lbs}}{\text{min} \times {}^\circ\text{F}}$

Since there are 12 inches in one foot, the factor 12 appears in the numerator.

Since there are 1/60 minutes in one second, the factor 1/60 appears in the denominator.

Since there are 1.8 degrees F in 1 degree C, the factor 1.8 appears in the denominator.

The factor is equal to $\frac{12}{1/60 \times 1.8} = 400$; 0.01 ft-lbs per sec per degree C is equivalent to 0.01 × 400 = 4 in-lbs per min per degree F.

Common Conversion Factors

Multiply the number of GIVEN units by the factor to obtain the number of REQUIRED units. The factor is numerically equal to the number of REQUIRED units in one GIVEN unit.

GIVEN UNIT	REQUIRED UNIT	FACTOR
ampere turns	gilberts	1.257
ampere turns per in.	gilberts per cm	.495
Btu	kg calories	.252
Btu	ft-lbs	.778
Btu	hp-hr	.0003927
Btu	Joules	1054.
Btu	kw-h	.000293
Btu per min	watts	17.57

GIVEN UNIT	REQUIRED UNIT	FACTOR
centimeters	inches	.3937
cm per sec	ft per min	1.97
cm per sec	miles per hour	.0224
circular mils	sq cm	$.5067 \times 10^{-5}$
circular mils	sq in.	$.7854 \times 10^{-6}$
cu cm	cu in.	.061
cu cm	gallons	.000264
cu ft	cu meter	.0283
cu ft	gallons	7.48
cu ft	liters	28.32
cu in.	gallons	.00433
cu in.	cc	16.39
days	min	1440.
days	sec	86440.
degrees (angular)	radians	.01745
dynes	grams	.00102
dynes	lbs	2.248×10^{-6}
ergs	Btu	$.949 \times 10^{-10}$
ergs	ft-lbs	$.738 \times 10^{-7}$
ergs	Joules	10^{-7}
ergs	kg calories	2.39×10^{-11}
feet	meters	.305
feet of water	in. mercury	.883
feet of water	lbs per sq ft	62.4
feet of water	lbs per sq in.	.434
ft per min	cm per sec	.508
ft per min	miles per hour	.01136
ft per sec	cm per sec	30.48
ft per sec	miles per hour	.682
ft lbs	Btu	.001286
ft lbs	ergs	1.356×10^{-7}
ft lbs	hp-hrs	$.505 \times 10^{-6}$
ft lbs	Joules	1.356
ft lbs	kg calories	.0003241
ft lbs	kw-hrs	$.3766 \times 10^{-6}$
ft-lbs per min	hp	$.303 \times 10^{-4}$
ft-lbs per min	kw	2.26×10^{-5}
gallons	cc	3785.
gallons	cu ft	.1337
gallons	cu in.	231.
gausses	lines per sq in.	6.452
gilberts	ampere turns	.796
gilberts per cm	ampere turns per in.	2.021
horsepower	Btu per min	42.44
horsepower	ft-lbs per min	33,000.
horsepower	kw	.746
in.	cm	2.54
in. of mercury	ft of water	1.133
in. of mercury	lbs per sq ft	70.73
in. of mercury	lbs. per sq in.	.4912
in. of water	in. of mercury	.0736
in. of water	lbs per sq in.	.0361
Joules	Btu	.000949
Joules	watt hours	.000278
kg	lbs	2.205
kg calories	Btu	3.968
kg calories	ft-lbs	3086.
kg calories	kw-hr	.001162
kw	Btu per min	56.92
kw	hp	1.341
kw	kg calories per min	14.34
kw-hr	Btu	3415.
kw-hr	Joules	3.6×10^{6}
kw-hr	kg calories	860.5
meters	ft	3.281
meters	in.	39.37
mm of mercury	ft of water	.0446
mm of mercury	lbs per sq in.	.01934
lbs.	dynes	4,444,823.
lbs.	grains	7,000.
lbs.	grams	453.6
lbs per cu in.	gr per cc	27.68
radians	degrees	57.3
rpm	degrees per sec	6.
years	hours	8760.

HOW TO TELL IF AN ENCLOSED MOTOR WILL PAY FOR ITSELF

Weighing initial costs and life expectancies of electric motors enables you to choose between open and enclosed type motors for maximum economy.

G. Byberg

MOTOR AND GENERATOR DIVISION • ALLIS-CHALMERS MANUFACTURING COMPANY

Wartime operating conditions will take the rap for many a motor's shortened life, but the answer to why one motor can operate 30 years while another is "old" and worn out after 30 days is still pretty much a matter of where the motor must *live*. Getting longer motor life, then, invariably means meeting adverse operating conditions by choosing motors that are especially built for the tough spots.

Is the motor you'll need worth the premium you'll have to pay for the extra protection? If the cost of an enclosed motor, for example, is several times that of a standard open type, will your particular conditions make such a choice economically sound?

Choosing motors need not be a guess or a gamble, but can be based on a reasonably accurate economic comparison. With exact data on operating conditions and cost comparisons such as are illustrated in the accompanying curves and tables, the problem of selecting the most economical motor is easy. For example, if it is assumed that the normal life of an open motor under good operating conditions is not less than 10 years, but that under the particular condition in question open motors have lasted only five years, the cost of an enclosed motor may be economically justified. If this were a one hp, 1,800 rpm motor, Fig. 1 indicates that a totally enclosed type would cost only 15 percent more than the open type, whereas rewinding the open motor after five years would represent a cost of 40 percent.

On the other hand, if a 100 hp, 720 rpm machine were being considered, a totally enclosed motor would cost 100 percent more, as compared with repair costs of approximately 25 percent for the open type after its five years in operation, justifying selection of the open type. However, a "life" of only one year, requiring rewinding of the open motor at least eight times in the ten year period, would leave no question about choosing the protected machine.

Typical adverse conditions

In general, the presence of injurious agents in the surrounding atmosphere, or the unavoidable collection of excessive amounts of dust and dirt in ventilating ducts and air passages, point to the possibilities of applying protected motors. Such severe conditions of installation frequently met are:

(a) Steam, or excessive moisture from vapor, splashing, dripping or flooding. These conditions are encountered in certain parts of dye houses, bleacheries, packing plants, paper mills, etc.

(b) Conducting or abrasive dusts, such as cast-iron, carbon, coke, graphite, etc., usually encountered in coal pulverizing equipment, carbon plants and grinding rooms.

(c) Combinations of conducting and abrasive dust, such as coke, carbon, coal, etc., with sulphur fumes, moisture, etc. These conditions are frequently encountered in power plant boiler rooms around fans, coal pulverizing and ash handling equipment, carbon plants, cement plants, etc.

Of course, insulation breakdown will probably mark the shortened life of a motor operating under any of these conditions. Consequently, when an open type motor lacking winding protection has a life as short as 30 or 40 days in an electro-chemical process application, for example, that short life can hardly be ascribed to faulty design. Obviously, the organic insulating materials cannot withstand the effects of certain injurious elements. So detrimental might such effects be, in fact, that even the non-active parts like the frame, bearings and brackets eventually deteriorate.

In cases where severe conditions are present, it is certainly false economy not to use suitably protected motors. For less severe conditions, many intermediate means of protecting open motors can be considered, since drip-proof, drip-proof protected, splash-proof and other types are available. However, for purposes of economic comparison, only the totally-enclosed type will be discussed in the considerations which follow.

Temperature rise

To begin with, a fair comparison of open type motors with enclosed types should consider that the 55C stand-

AT LEFT: Bank of three-winding, 13,333 kva, 110 kv powers transformers serving many war industries in the Pacific northwest.

Horsepower	1	1½	3	25	100	350
Revolutions per minute	1800	1200	1200	900	720	514
List price, open type	$35	$49	$67	$292	$937	$3,000
Percent of list price for rewinding; set of stator coils and rewinding material, express charges, disassembly, removing old windings, cleaning, rewinding and reassembly of the open motor, approximately	40%	35%	33%	27%	25%	25%
List price totally enclosed (non-ventilated) 55C rise motor	$40	$68	$117	$875	Not built	
Cost of non-ventilated motor in percent above open 40C rise motor price (Fig. 6)	15%	37½%	75%	200%	Not built	
List price totally enclosed fan-cooled 55C rise motor	Not built		$100	$495	$1,873	$7,045
Cost in percent above open 40C rise open motor (Fig. 13)	Not built		50%	70%	100%	135%

Fig. 1 — Pertinent cost data on standard normal torque, normal starting current, squirrel-cage induction motors designed for 3-phase, 60-cycle, 440 or 550 volt operation. Economic comparisons can be made without knowing exact dollar prices of motors, since the ratio of cost is the desired value and this is shown in accompanying curves.

ard temperature rise of the latter is not objectionable even though the corresponding standard rise of open motors is 40C. Actually, the difference between the observable temperature rise and the hot spot temperature in an enclosed motor is five degrees less than in an open motor, because of better internal distribution of heating. Then too, while an open motor may have a temperature rise of 40C when tested as a new, clean motor, after operating in an extremely dirty or dusty atmosphere for a long time (as in Fig. 2), its temperature may be considerably increased. If dirt and dust clog the ventilating passages in the windings, the resulting impaired ventilation may cause the temperature rise to go well beyond the rated value and even exceed that of the enclosed type of machine.

Fig. 2 — Dirt, water, and oil completely cover this motor, operating under extremely adverse conditions where a protected motor would obviously be economical.

Totally-enclosed motors

Defined by A.S.A. standards as "a motor so enclosed as to prevent exchange of air between the inside and the outside of the case, but not sufficiently enclosed to be termed air-tight," the totally-enclosed machine is characteristically without direct ventilation, hence dependent upon radiation for cooling.

As a result, the frame size of the enclosed motor for a given continuous rating and speed may be from two to six frames larger than for an open motor for the same horsepower rating and speed. The graph in Fig. 3 indicates approximately the ratios of frame size between open type 40C rise motors and enclosed type 55C rise motors of the squirrel cage, normal torque, normal starting current type, at speeds of 850 to 1,750 rpm. It will be noted that there is an appreciable increase in the output per frame size for lower speeds. For example, a 25 hp open motor frame is required at 1,750 rpm for a 7½ hp enclosed motor, while at 850 rpm the 25 hp open motor frame is good for 10 hp, enclosed, because of the greater frame size and increase of radiating surface. However, further decrease in speed will not result in correspondingly lower ratio between open and enclosed frames, because with decreasing power factor in the lower speed motors the kva input is not correspondingly reduced.

For industrial service this construction is generally confined to the smaller sizes of general purpose ratings, up to approximately 15 hp, 55C rise continuous, or 200 hp, short-time rated (15 to 30 minutes). This classification also includes motors for metal-rolling mill auxiliary service, street railway, mine haulage locomotives, crane and hoist service, and electric shovel service.

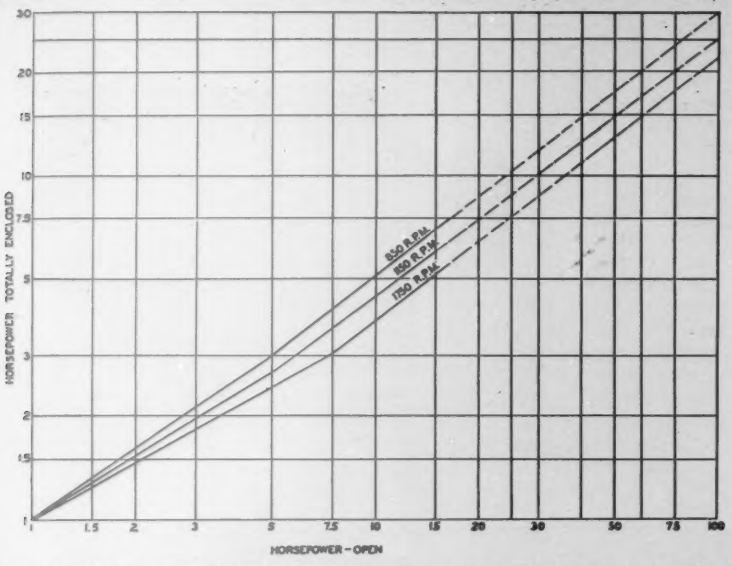


Fig. 3 — Approximate ratios of frame size between open type 40C rise motors and enclosed type 55C rise motors of normal torque, normal starting current type, at speeds of 850 to 1,750 rpm.

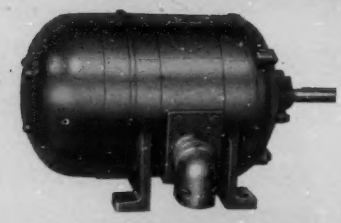


Fig. 4 — Small, enclosed type d-c motor.

Fig. 5 — Enclosed, non-ventilated, squirrel-cage motor for general industrial service.

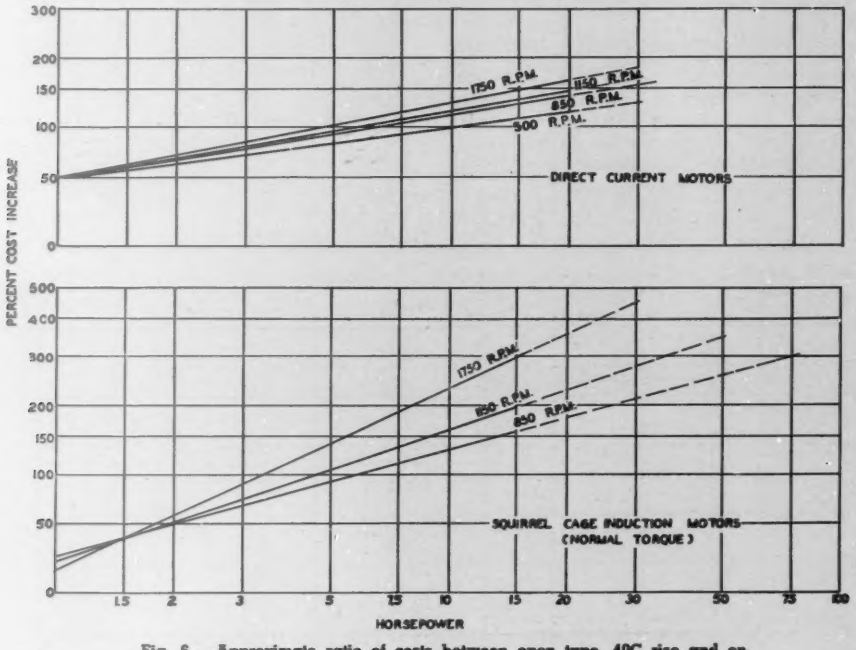


Fig. 6 — Approximate ratio of costs between open type, 40C rise and enclosed type, 55C rise motors of both squirrel-cage and direct-current design.

Fig. 4 shows a small direct-current motor and Fig. 5 a squirrel cage motor, of the enclosed type for industrial service.

The approximate ratio of costs between open type 40C rise and enclosed type 55C rise motors of both the squirrel cage and direct-current type is shown in Fig. 6. It will be seen that the ratios for direct current motors differ considerably from those of squirrel cage motors. This is because, primarily, the open type d-c motors are inherently higher in cost than open type squirrel cage motors and consequently the enclosed types are a lesser percentage of the open motor cost. In addition, the full-load efficiencies of the smaller d-c motors are somewhat lower than those of the squirrel cage motors, which condition reacts a little less favorably upon the ratio between open and enclosed machines.

Totally-enclosed, fan-cooled motors

"A totally-enclosed, fan-cooled motor is a totally-enclosed machine equipped for exterior cooling, with a fan or fans integral with the machine but external to the enclosing parts," according to A.S.A. standards.

Cutaway and external views of machines of this

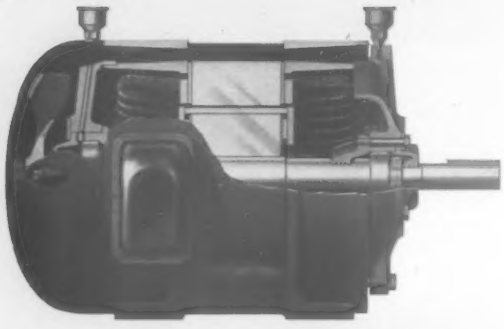


Fig. 7 — Air passages in a totally-enclosed, fan-cooled, squirrel-cage motor are shown in this sectional view.

Fig. 8 — Collector-ring enclosure can be seen on this totally-enclosed, fan-cooled, wound rotor motor.

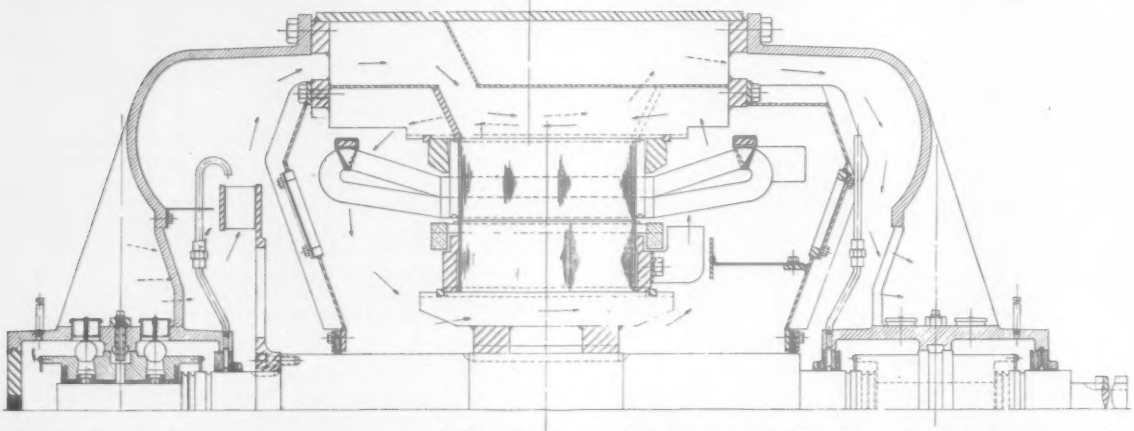


Fig. 9 — Method of ventilating a typical fan-cooled, sleeve bearing, squirrel-cage motor (like Fig. 10) is detailed in this cross-section.

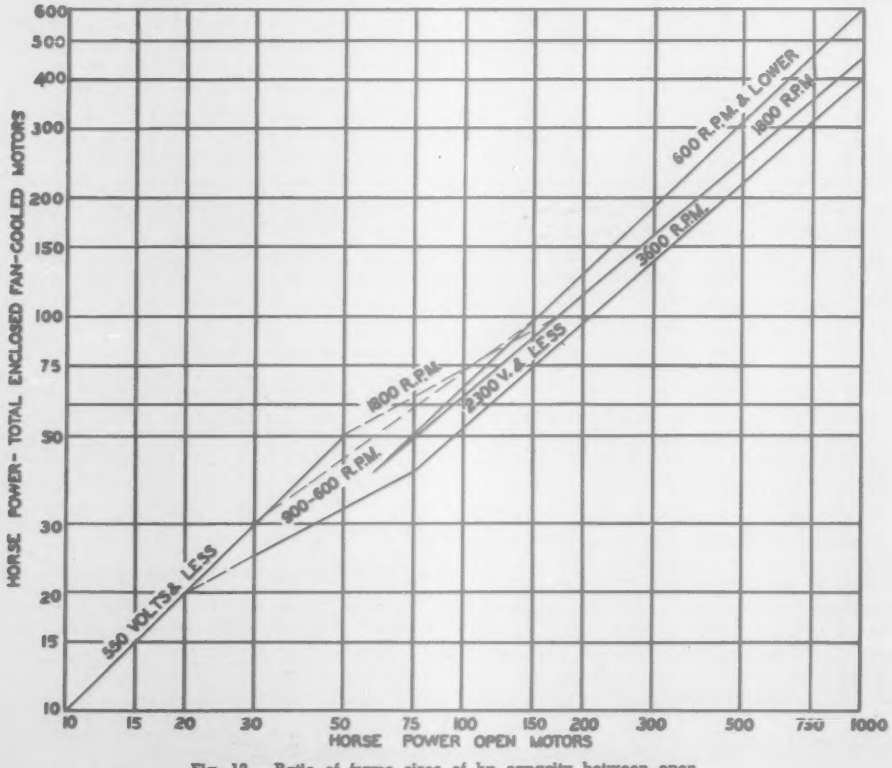


Fig. 12 — Ratio of frame sizes of hp capacity between open type, 40C rise motors and fan-cooled motors rated 55C rise.

Fig. 10 — High-speed, totally enclosed fan-cooled squirrel-cage motor with sleeve bearings.

Fig. 11 — Intermediate speed, cage motor with anti-friction bearings.

type having standard construction are illustrated in Figs. 7, 8, 9, 10 and 11.

For industrial service, the fan-cooled type is built in squirrel cage and wound-rotor induction motors for speeds from 500 to 3,600 rpm and in unity power factor synchronous motors from 500 to 1,800 rpm. Ratings up to 500 or 600 horsepower are quite common and even larger machines are used under favorable conditions. As bracket bearing machines, they are limited to approximately 0.75 to 0.5 hp per rpm, depending upon speed. For speeds below 500 rpm, it is usually not possible to build the smaller horsepower ratings because of insufficient fan-action, but for certain conditions it has been found practicable to build larger sizes for speeds as low as 300 to 360 rpm.

Fig. 12 shows the approximate ratio of frame sizes of hp capacity between open type 40C rise motors and the 55C rise fan-cooled type.

The approximate cost ratio between open type 40C rise and the 55C rise fan-cooled machines of the squirrel cage type is indicated in Fig. 13.

Special features available

Both the totally enclosed and the totally enclosed fan-cooled motors are available for operation in certain classes of explosive atmospheres at an increase in cost, varying from 50 percent for the smallest to 7½ percent for the largest, over that of the standard enclosed motors. Figs. 13 and 14 show induction motors of this type. Totally enclosed fan-cooled and explosion-proof motors for outdoor operation are available at

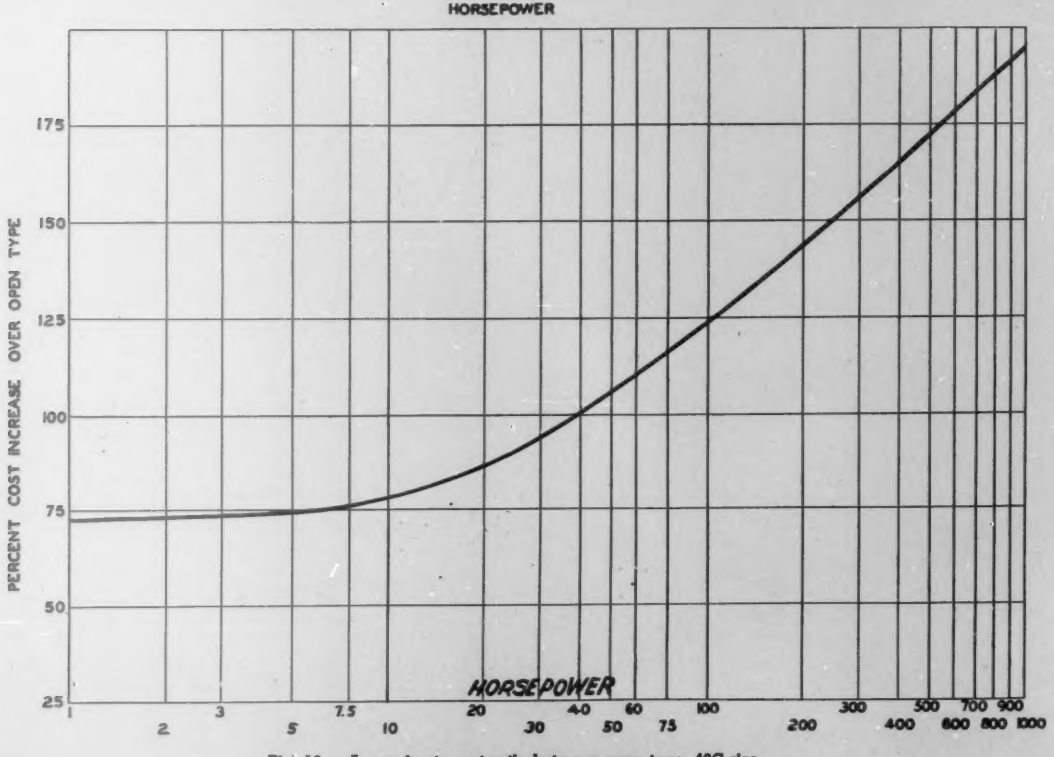


Fig. 13 — Approximate cost ratio between open type, 40C rise motors and the 55C rise, fan-cooled, squirrel-cage machines.

an increase in cost of from 7½ to 26 percent over that of explosion-proof motors. Also, either type can be built watertight at an increase in cost varying from 6 to 10 percent over that of an explosion-proof motor.

The efficiencies of enclosed type motors will usually be very nearly the same as those of the open type of the same rating in larger sizes. For smaller sizes, the efficiency of the enclosed motor will be somewhat less. As the rating increases and as the frame sizes increase at a faster rate, it is possible to operate at reduced core loss and copper loss, and even though the windage losses increase, the total results approach within a fraction of percent of the efficiencies of the open motor at full load.

Conclusion

By making comparisons based on operating data and statistics like those in Fig. 1, it can be readily determined which motor type is best suited for a specific application from an economic standpoint. Frequently, "more expensive" enclosed motors will be found to be money-savers in the long run.

Aside from the consideration of initial cost and maintenance, the matter of keeping that motor in operation is often a real factor in favor of the enclosed motor. If frequent shut-down seriously interferes with a whole section of the plant, loss of production would certainly justify paying more for a motor that could operate longer under adverse conditions without needing repair.

Fig. 14 — Totally enclosed, non-ventilated, explosion-proof motor — one horsepower.

Fig. 15 — Totally enclosed, fan-cooled, explosion-proof motor — 150 hp — 440 volts, 1800 rpm, 3 phase, 60 cycle.

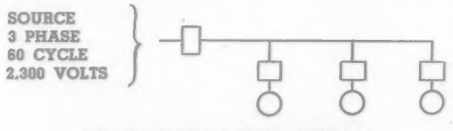
WHAT'S THE ANSWER?

Question— Why are low voltage air circuit breakers rated in R.M.S. amperes and high voltage oil circuit breakers rated in kva? — R. C. H.

Answer— On low voltage breakers the maximum current to be interrupted determines the breaker design, and variation of the voltage within the limits of standard service voltages does not materially affect the performance of the breaker.

On higher voltage breakers, however, there is both a maximum current and a maximum kva limitation, and consequently these breakers are rated to interrupt a maximum kva, but not in any case to exceed a certain maximum current. Both values are given in the rating tables. — H. V. N.

Question— We are planning the installation of metal-clad switchgear in a pumping station. The pumps are to be driven by synchronous motors at 2,300 volts, 3-phase, 60-cycles (the supply voltage). The incoming line has a possible short circuit value of 49,500 kva. There will be three synchronous motors each rated 500 hp, 327 rpm. What capacity circuit breakers should be installed on the incoming lines and feeders? — A. E. K.



500 HP SYNCHRONOUS MOTORS

Answer— The incoming line breaker would be required to interrupt 49,500 kva for a short circuit on its load side. If a short should occur on the source side and it were equipped with straight overcurrent or reverse current relays, it would only have to open the short circuit current generated by the three synchronous motors. This is determined by the size and speed of the motors, which in this case would likely be about 2½ times full load current. Assuming 80 percent power factor motors, this would amount to about 3,900 kva for the three motors.

Any one feeder breaker, opening on a short circuit on the feeder it protects, may have to open not only the current coming from the line, but also the short circuit current from the two other synchronous motors. Thus, each feeder breaker should be capable of interrupting 49,500 kva plus 2,600 kva, or a total of 52,100 kva.

Consequently, although a 50,000 kva breaker would do for the incoming line, the feeder breakers should be the next larger size, which is 100,000 kva. Usually all three would be made the same size. — T. G. A. S.

"What's the Answer?" is conducted for the benefit of readers of ELECTRICAL REVIEW who have questions on central station, industrial or power plant equipment. Send all questions to the Editors of ELECTRICAL REVIEW.

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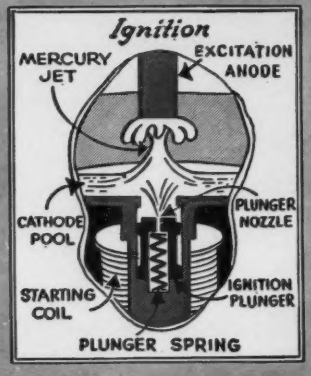

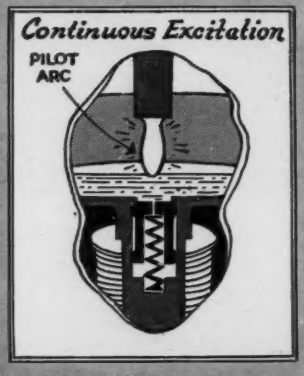

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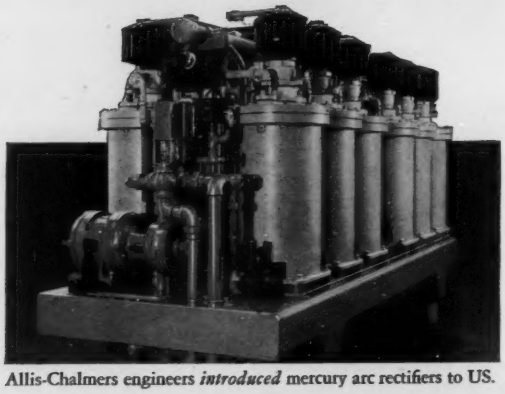

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